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Efficient and effective irrigation in the Wairarapa: results from field monitoring

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Abstract

Although irrigation is essential for agricultural production in the Wairarapa, water resources are already limited in a number of areas and are acting as a constraint on development (Morgan, 2000). This study was conducted to quantify the actual need for water to maintain pasture production. Currently, at high application rates, much of the water flows through the macropores in the soil, quickly bypassing the root zone, thus simply recharging the groundwater. This costs the farmer money with little return in terms of increased productivity. This study will allow allocations to be "tailored" to specific situations.

The effects of different irrigation systems and different soil types on soil moisture availability and drainage were investigated around Greytown. The soils of the Wairarapa valley are dominantly of alluvial origin. Recent-well drained soils have deep profiles, good structure, high water storage capacity, and plant-available water over a wide range of moisture contents. Gley and Recent-poorly drained soils have similar properties, but lower hydraulic conductivity and plant-available water capacity. Yellow-grey earths have a moderate water capacity, but their critical water content is high. Yellow-brown stony soils, common on upper terraces, have high hydraulic conductivities and thus transmit water very quickly. In addition, these gravelly soils have a low water storage capacity. These differences in water storage potential and availability must be considered when assessing agricultural water needs. Consequently a total of 20 irrigation runs, covering a range of soil types and irrigation systems (spray-gun, border dyke, multi-head), were monitored. The amount and intensity of irrigation was monitored with tipping bucket raingauges. Campbell Scientific TDR (Time-domain reflectometry) soil water content reflectometers were used to monitor soil water storage and transmission.

The intensive monitoring of soil moisture storage and water movement throughout the soil profile showed distinct differences between the soil groups. This variability, combined with the spatial distribution of effective precipitation, means that no single irrigation solution will meet crop water needs throughout the region. Spray irrigation is often used to maintain pasture production. However, spray application intensity, duration, and the total amount applied must take into account the ability of the soil to store this water and transmission rates through the profile. In general, low intensity spray methods applying little water often are more successful, particularly on soils with high hydraulic conductivity. However, too much water is often applied with these systems. The application of greater amounts of water does not necessarily equate to an increased duration of readily available water. Efficient and effective irrigation requires tailoring the irrigation type and regime to specific soil characteristics and crop water needs. Although there is no one "ideal" irrigation system for the Wairarapa, encouragement should be provided for a move to a lower intensity, and a low total application depth, with the ability to irrigate more frequently. Detailed field monitoring can provide the information necessary for a "designer" consent which promotes efficient and effective water management. This information also provides the necessary information to assess the consequences and effects of the irrigation as required by the Resource Management Act (1991) .

Introduction

Irrigation in the Wairarapa occurs on land with a range of soil types and diverse land uses, from horticulture and orchards through to pasture growth for dairying. Use of much of the land area, and many of these practices, would not be possible without irrigation during the summer months. Although irrigation is essential for maintaining agricultural production in the Wairarapa, water resources are already limited in a number of areas and they are acting as a constraint on development options and future human activities. Indeed, it is unlikely that significant amounts of water will be available for allocation from surface water resources. While groundwater may be available in many areas, the yield from most of these zones is very low (Morgan, 2000). Existing allocation practices, based essentially on demand and the size of the water resource, are increasingly leading to conflict. This situation is likely to get worse with further intensification and diversification of land use (such as the increase in dairying). This problem is compounded by the "traditional" nature of much of the irrigation in the Wairarapa. Some of these "old" practices can no longer be regarded as using the limited water resources either efficiently or effectively, and their continued use is being questioned. Climatic variability, including that relating to the Southern Oscillation, compounds this problem. A recent report (Harkness, 2000) suggests that La Nina conditions during summer are linked to low autumn rainfall, while El Nino conditions during spring result in low summer rainfall. Current irrigation practices may also be hard to justify at an Environment Court, or other hearing under the Resource Management Act (1991), since it could be argued that they do not lead to the sustainable use of resources.

At present approximately 77% of the water allocated for a consumptive use is for irrigation. As in much of New Zealand, water for irrigation in the Wairarapa is allocated on the basis of a perceived water-need; i.e. based on estimated evaporation losses of around 5 mm/day (Dravid *et al.*, 1995; Lincoln Environmental, 2000a). Allocation is not "tailored" to specific situations, or anticipated outputs. Thus neither the land use nor soil factors are considered, and there is no incentive for farmers to use less water than allocated. At high application rates much of the irrigation water flows through the macropores in the soil, quickly bypassing the root zone, and simply recharges the groundwater. This costs the farmer money, with little return in terms of increased productivity. In addition, over-application increases the leaching of pesticides and fertilizers and hence the risk of groundwater contamination. At the same time it decreases the water resources available to others, for no benefit. Waste may also occur if the irrigation water evaporates before being used by the crops. Understanding the irrigation requirements of crops on the various soils in the study area, as well as the most efficient method of applying this water, are therefore of critical importance to the long-term management of the water resources (Beanland *et al.*, 1994; Hillel, 1998).

As noted by Watt *et al.*(1995) there is considerable scope for "designer consents", which match soil hydraulic properties, crop water demands, and optimal irrigation management. The soil hydraulic properties, i.e. porosity, bulk density, hydraulic conductivity, permeability and the character of the moisture retention curve, and the irrigation system together affect the amount and nature of the water stored. The pores of the soil can hold a limited store of water. When inputs of water to the soil surface exceed evapotranspiration outputs the storage is recharged, and when evaporative losses exceed inputs the soil moisture acts as a buffer to reduce stress on the plants. Irrigation is 'required' when the "effective rainfall" (rainfall minus evapotranspiration losses) and the soil moisture storage are such that plants suffer water stress. With the addition of crop type, these properties also affect how much of this water is available for plants, and how long this water remains plant-available, and hence the 'irrigation efficiency'. With the aim of promoting effective and efficient water management, this paper examines the relationships between soil hydraulic properties, irrigation systems, and the soil-water response.

The study area

This paper concentrates on an area bounded by the Rimutaka and Tararua axial ranges to the west, the Aorangi Range to the east, and extending from the south coast to Mt Bruce in the north. Within this area the steep forested slopes of the ranges give way to the low lying and relatively flat inland plain which is used almost exclusively for agriculture and horticulture. Intensive irrigation occurs around Greytown and it is the response of the soils in this area to irrigation which is the focus of this paper (Fig. 1).

Within the central Wairarapa the New Zealand Land Resource Inventory recognised 50 soil types (Newsome, 1992); however, it was possible to combine these into 9 groups on the basis of their hydraulic properties and behaviour (Hawke *et al.*, 2000b). The differences in the soil physical and material properties between these soil groups affect the amount of soil water storage, the availability of this water to plants, and their likely response to the application of irrigation water. Rather than rely on the results of laboratory tests and modelled responses, this paper discusses the actual physical response of the soils to irrigation monitored in the field.

Data collection

The Wellington Regional Council (WRC) database of consents was linked to the soil classification scheme developed for this study (Hawke *et al.*, 2000b) to assess the relative importance of both the type of irrigation, and the soil being irrigated. Within the Wairarapa there were 350 active consents; however, only 278 of these were within the study area (i.e. on "classified soils"; Table 1). This is likely to be an underestimate of the actual number of water users, since consent holders can continue to extract water during the consent renewal process.

Table 1 highlights the dominance of spray irrigation. This is the technique of choice for many of the regions' dairy farmers. Horticulturalists and orchardists tend to favour trickle irrigation. A few farmers, generally those on more established properties, use border-dykes or wild flooding.

Monitoring the soil's response to irrigation started during the 1998-99 summer. Sites were selected to be representative of the different soil groups. Consequently, sites were chosen away from any soil group boundaries, and a profile examination ensured that each site was typical of its particular soil group (Hawke *et al.*, 2000b). The study sites were all under pasture, because this land use entails the largest consumptive use of water in the Wairarapa (Wellington Regional Council, 2000).

Since the ability of roots to access soil water is determined by the soil water potential (tension), tensiometers have traditionally been used for irrigation scheduling. However, these devices only operate over the moist

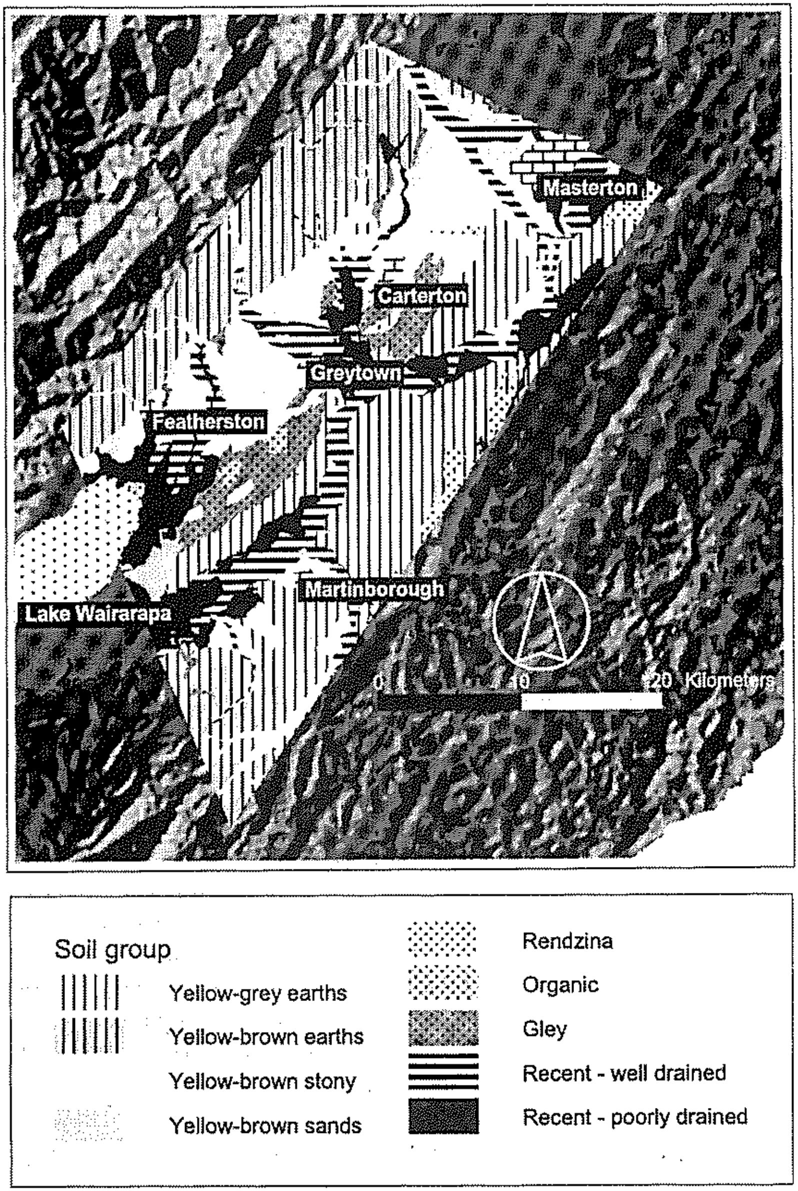

Figure 1 – The study area. Within the central Wairarapa region the 50 soils recognised by the NZLRI can be grouped into 9 soil groups on the basis of their hydraulic properties. Each soil group responds to irrigation in a different manner.

(0-0.85 bar) range. Time-domain reflectometry allows rapid, real-time, repeatable, and non-destructive monitoring of soil water content over the entire range observed in the field, and the signals can be recorded digitally. While time-domain reflectometry (TDR) has yet to become the irrigation industry standard, it has become the most accepted method for soil physicists, eg. Hillel, 1998; *cf* recent issues of *Soil Science Society of America Journal*. Campbell Scientific CS-615 TDR soil water content reflectometers were therefore used for this study.

Table 1 – The distribution of irrigation consents with respect to soil group and irrigation type

Soil Group[1]	Irrigation Type						
	Border dyke	Sub-surface	Spray	Trickle	Wild flooding	Un-classified	Total
Yellow-grey earth	0	0	7	3	0	1	11
Yellow-brown stony	1	1	48	17	0	6	73
Yellow-brown sands	0	0	3	1	0	0	4
Organic	0	0	1	0	0	0	1
Gley	0	2	24	2	1	2	31
Recent – well drained	1	0	56	25	0	6	88
Recent – poorly drained	1	2	58	5	0	4	70
	3	5	197	53	1	19	278[2]

Notes: [1] Soil groups are those described in Hawke *et al.*, 2000b (no irrigation consents are currently issued for areas on Yellow-brown earths and Rendzinas)

[2] At least 278 consents, with a total allocation of approximately 400,000 m^3/day.

At each monitoring site soil water content reflectometers (probes) were installed at depths of 100 mm, 250 mm, and 500 mm. A further probe was installed vertically to give an integrated measure of the volumetric water content within the upper 300 mm of the profile. The most likely sources of error associated with TDR measurements are due to poor installation. Therefore a frame was constructed to ensure that the probe wires were installed straight and parallel, and the holes were drilled slightly undersize to ensure there was a good contact between the soil and the probes (with no air gaps). To calibrate the probes, readings were compared to gravimetric samples and the greatest value recorded was compared to the gravimetrically determined porosity. The probes at each site were connected to a Campbell Scientific datalogger. Since 500 mm is generally below the base of the root zone of pasture, at least in the study area (field observations; Green *et al.*, 1996), this configuration allowed the continuous monitoring of both the plant-available water, and any water lost from the root zone. To maximise the temporal resolution of the data, while minimising data storage requirements, the dataloggers were programmed to record the soil water content every 5 minutes, but only if the measurement was more than 0.2% different from the last recorded measurement. The intensive instrumentation not only allowed the continuous monitoring of soil water content, and changes through the profile, but also the timing of water flow. For the irrigation water to be available to the grass it needs to remain within the root zone i.e. the upper 500 mm of the soil profile. Therefore, as a first estimate, if the TDR probe at 500 mm shows an increase in soil water content following irrigation, this indicates water is flowing past the root zone and will not be available to support grass growth i.e., the water is being wasted.

To ensure that the results were representative the probes were left at each site to record the responses during at least two complete 'irrigation runs'. The 1999-2000 summer, while not unusual in terms of the total amount of rainfall (85 mm of rainfall was recorded in January at our climate station in Greytown compared to a mean of approximately 70 mm), was a poor one from an irrigation monitoring point of view. Rainfall occurred on such a regular basis (between December 1999 and 28 February 2000 there were 36 days of greater than 0.1 mm rain) that many farmers rarely had to irrigate (various farmers, *pers. comm.*, 2000). At a couple of sites no irrigation water was applied over the entire summer. While the 85 mm of rain recorded in January was slightly above average, many irrigators apply 60-70 mm of water during each 'irrigation run' and these 'runs' are made 10–14 days apart.

Despite difficulties caused by the atypical summer conditions, 20 irrigation runs were monitored. These cover the major soil groups and the dominant irrigation techniques (Table 2). The data collected confirmed that the amount of irrigation water applied, the duration of irrigation, and the method of application are all highly variable. Hence, while water need is a function of prevailing weather conditions, crop type and growth stage, it is the individual farmer who currently exerts control over the nature of irrigation, and as a result the water demand.

Results

A typical response to irrigation is shown in Figure 2. This figure shows the response of a Yellow-brown stony soil to 21 mm of irrigation over a 3-hour period. The soil water content at 100 mm, while increasing during actual irrigation, remained low. This is because of the high percentage of stones at this depth and therefore the low percentage of available pore space. Such

Table 2 – Summary of the monitored irrigation runs

Soil group	Site	Irrigation type	Amount applied (mm)	Duration of irrigation (min)
Yellow-grey earth	9	Multi-head	43	1178
			55	1403
	12	Spray-gun	57	255
			18	127
	15	Multi-head	70	1385
Yellow-brown stony	3	Spray-gun	21	162
			30	151
	13	Multi-head	215	1433
			188	1329
Gley	14	Spray-gun	28	226
Recent-well drained	1	Rotating boom	35	342
			25	271
	2	Border-dyke	75	270
			75	270
	10	Spray-gun	35	251
	11	Multi-head	51	562
Recent-poorly drained	4	Spray-gun	21	119
			29	110
	5	Multi-head	61	538
			28	736

soils also drain very rapidly. Within 30 minutes the water had percolated to 250 mm and within 60 minutes to 500 mm. At 250 mm the soil water content rose rapidly until saturation; however, the soil started to drain as soon as irrigation stopped. Within 6 hours of irrigation the soil water content was almost back to the pre-irrigation level. At 500 mm the soil water content remained close to saturation for nearly 12 hours before draining. Two days after irrigation 15 mm of rainfall fell over a 20-hour period. This water also reached a depth of 500 mm rapidly, had a short term effect on the soil water content at 100 mm, but virtually no effect on the soil water content at 250 mm. It appears that this soil type behaves essentially as a "sieve", with the water moving rapidly past the root zone. Much of the applied water is therefore lost before it can support grass growth.

A very similar pattern was observed during the next irrigation cycle (Fig. 3). Within an hour of irrigation a response was recorded at 500 mm. Within 16 hours of irrigation the soil water content at all three depths was back to its pre-irrigation level. Five millimetres of rain a day after irrigation caused virtually (within a few percent) the same response in the soil water content at 100 mm as the 30 mm of water applied by the irrigation gun. The stony nature of the soil at this site means that only a very small amount of water is required to fill the available pore space. Even at low moisture

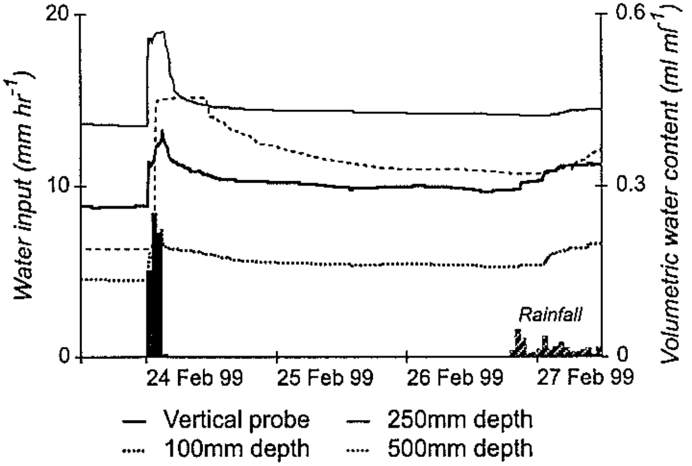

Figure 2 – The soil moisture response of Yellow-brown stony soil to spray-gun irrigation (February, 1999). This soil responds rapidly to 21 mm of irrigation. Within 6 hours of irrigation; however, the soil water content at 250 mm is back to its pre-irrigation level.

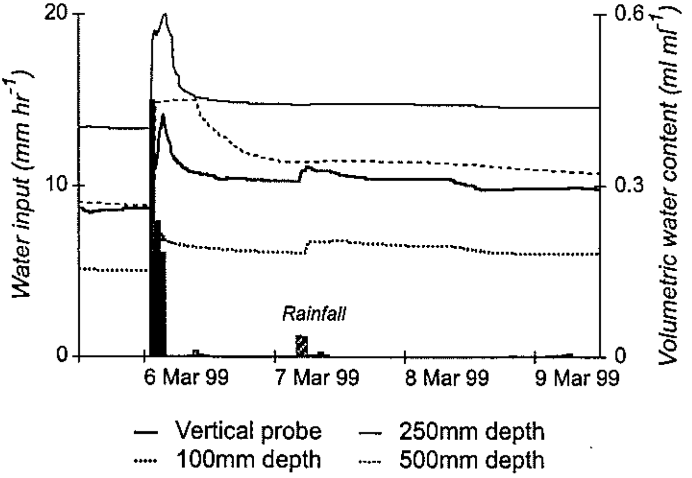

Figure 3 – The soil moisture response of Yellow-brown stony soil to spray-gun irrigation (March, 1999). Comparison of this figure with Figure 2 shows the consistent response of the soil to each irrigation cycle, and the highly reproducible nature of the results.

contents any moisture drains through the profile very rapidly under the influence of gravity because of the large pore size, which exert tensions too low to retain moisture. In this case applying 21 mm of water had the same effect as 30 mm of water, i.e. the extra 9 mm of water was 'unnecessary', a potential saving of 90 m^3 of water per hectare per irrigation run.

From the detailed data collected from each of the irrigation runs (Table 2), the soil moisture response could be analysed. The rate at which the soil 'wets up' in response to irrigation is a function of both the soil properties (i.e. its bulk density, pore size distribution, porosity, hydraulic conductivity, and antecedent moisture status) and the type of irrigation method (especially the rate of application). Therefore one has to be careful to differentiate between the two sets of controls. However, once irrigation has ceased the rate at which water is redistributed within the profile is controlled solely by the soil properties. One way to quantify the differences between the soils, and the extent to which the soil controls the response to irrigation, is to examine the shape of the soil water content decay curve after the maximum soil water content is reached.

Following irrigation, water drains from the largest pores first, as they exert the smallest capillary forces. As a result the soil water content decreases rapidly. Therefore the higher the percentage of large pore spaces, and assuming water can drain from the base of the profile, the steeper the gradient of the 'drying curve' (Table 3). As anticipated from the physical properties of the Yellow-brown stony soil, i.e. the very coarse and stony nature of the whole profile, this soil has the steepest drainage curve. However, it is interesting to note that the Gley soil drained at approximately the same rate. This was because of the very gravelly nature of the lower profile of the gley soil. It was therefore easy for water to move through this part of the profile. The slowest draining soil was, as expected, the Yellow-grey earth. These soils have a high bulk density and a high clay content, which is reflected in an abundance of small pores and low permeability (Hawke *et al.*, 2000b). While these soils can store a lot of water (high saturated soil water contents and porosity) the water within the soil is only slowly redistributed. Between these two extremes are the Recent-well drained and Recent-poorly drained soils. The Recent-poorly drained soils drained faster than the Recent-well drained soils; however, this is not as odd as it sounds. The Recent-poorly drained soils are classified not on the basis of their drainage characteristics within the upper 300 mm of the profile but by their drainage at depth. The Recent-well drained soils are generally deep silt loams and sandy loams and thus (because of their depth) have the ability to store a considerable amount of water. While having a lower gradient drying curve, the sandy nature of this material means the water is not held by large capillary forces

Table 3 – Observed rate of decline of the soil water content in the top 300 mm of profile

Soil group	Irrigation type	Gradient of the drying curve[1]
Yellow-grey earth	Multi-head	-0.007
		-0.012
		-0.016
		-0.009
	Spray-gun	-0.008
		-0.006
Yellow-brown stony	Multi-head	-0.059
		-0.048
	Spray-gun	-0.056
		-0.091
Gley	Spray-gun	-0.056
Recent-well drained	Border-dyke	-0.010
		-0.012
	Multi-head	-0.010
	Rotating boom	-0.011
		-0.010
	Spray-gun	-0.015
Recent-poorly drained	Multi-head	-0.039
	Spray-gun	-0.028
		-0.055

Notes: [1] The gradient of the observed change in soil water content of the top 300 mm of the soil profile after the maximum soil water content was reached

(unlike the Yellow-grey earths) and so the water is available to plants over a wide range of moisture contents.

The TDR installations used in this study allow the determination of the *in situ* hydraulic conductivity. Hydraulic conductivity was assessed as the time difference between the increase in soil water content at 100 and 500 mm depths divided by the spacing of the probes. While the ranking of the soil groups on the basis of their field values are in the same order as those based on either the Guelph permeameter or the laboratory data, the actual values are considerably greater (Table 4). The data also show that the method of irrigation exerts considerable influence on the rate, and processes, by which water moves through the soil profile. Under border-dyke irrigation, for example, there is a very rapid response at 500 mm as the water is moving through the macropores. Thus the "effective" hydraulic conductivity is very high. These site-to-site differences can only be quantified with detailed field measurements; however, the laboratory measurements are useful in assessing the relative differences between the soil groups.

Table 4 – Comparison of laboratory determined near-saturated (K_{-40}), field-saturated hydraulic conductivity (Guelph permeameter), and the 'hydraulic conductivity' determined from the timing of the wetting front passing the TDR probes at 100 and 500 mm depths

Soil Group	Laboratory determined near-saturated hydraulic conductivity (mm hr^{-1}) 100 mm depth	250 mm depth	Field saturated hydraulic conductivity (mm hr^{-1}) 100 mm depth	Field (TDR) estimated hydraulic conductivity (mm hr^{-1}) 100 - 500 mm
Yellow grey earth	1.5 - 19.9	1.7 - 4.2	3.9	23 – 320
Yellow brown stony	7.5 - 10.7	5.7	31.3	60 – 1600
Gley	2.2	3.5	3.4	320
Recent - well drained	1.3 - 11.8	0.4 - 11.1	14.6	67 – 2400
Recent - poorly drained	10.9 - 18.7	6.6 - 13.8	11.6	200 – 267

The effect of different soil groups on soil moisture and drainage

The effect of the different soil properties on the response to irrigation can be seen in Figure 4. Between 25 and 30 mm of water was applied (by various techniques) to all soils, but the responses of the top 300 mm are quite different. The Yellow-grey earth absorbed the water even though it already contained 0.45 ml ml^{-1}. Once the soil was wet, its soil water content remained elevated. In contrast, the Gley and Yellow-brown stony soils responded rapidly, but then the soil also drained rapidly. The Recent soils responded rapidly but drained slowly. Thus, despite the amount of water applied being very similar, the nature of the response was quite different and can be related to the soil physical properties, i.e. the open and porous nature of Yellow-brown stony and Gley soils, the fine-grained nature of the Recent soils, and the clay-rich nature of the Yellow-grey earths.

The plots of soil water content against time can also be used to assess how long the soil water content remains elevated following irrigation, i.e., how effective the irrigation is in prolonging water availability for plant growth. The application of a large amount of water does not necessarily result in water being available to plants for longer, i.e., a considerable amount of the applied water may be lost by drainage through the soil profile. This is a waste of water, and it may also cause leaching of nutrients from the profile. For example, the open and porous nature of the Yellow-brown stony soil means that the water drains through this soil very quickly, and thus the addition of large amounts of water does not result in long-term water availability. However, the large moisture-holding capacity of the Yellow-grey earth means that this soil does have the ability to store the large amounts of water applied.

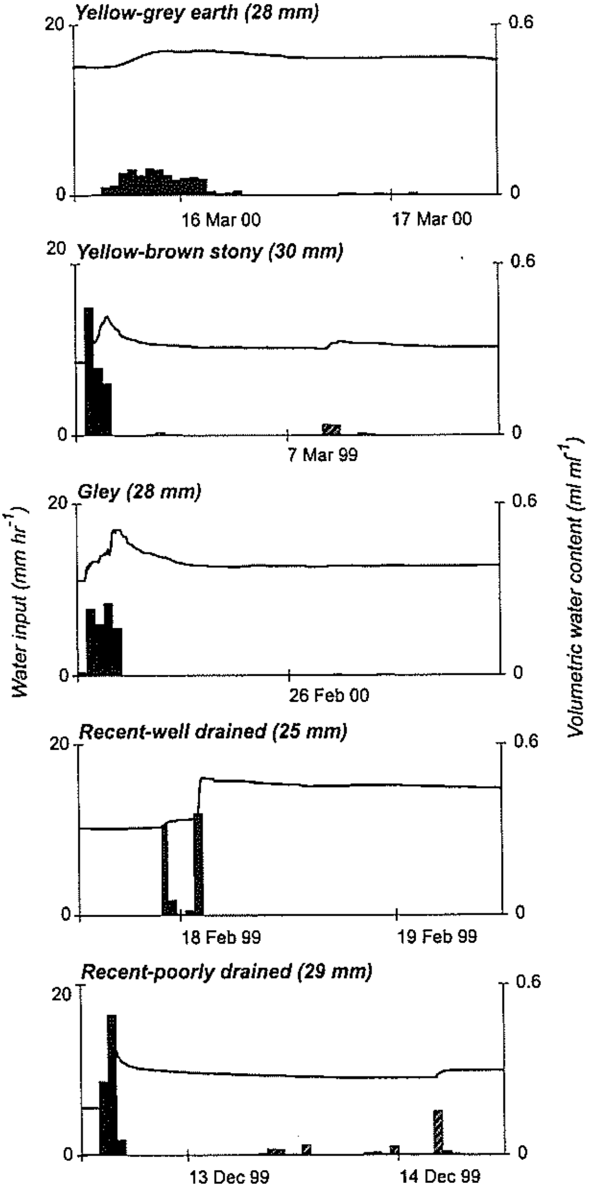

Figure 4 – The soil moisture response (the integrated volumetric water content of the top 300 mm of the soil) of the various soil groups to 25 - 30 mm of water. Despite a similar amount of water being applied, the responses were quite different because of the soils' physical properties.

The nature of the soil water content, at various depths, following irrigation can be assessed by using the ratio of the actual soil water content to the saturated soil water content (Table 5). For the Yellow-grey earth, irrigation water was applied when the soil water content dropped to 55% of the saturated water content at 100 mm depth. In all cases irrigation increased the soil water content to saturation. This water then drained only slowly. Five days after irrigation the minimum soil water content was still 67% of the saturated value. Given Site 9 had a relatively stony upper profile, the ability of this soil to retain water is shown in the soil water contents (90% of saturation) 48 hours after irrigation. The difference between the Yellow-grey earth and Yellow-brown stony soils can be seen in the decline in soil water contents 48 hours after irrigation, i.e. 80% compared to 90%. The Gley and Recent soils remained very close to saturation for the first 48 hours after irrigation and then the soil drained to around 85% saturation after a week.

Table 5 – Changes in the soil water content at 100 mm depth following irrigation

Soil Group	**Site**	$\theta_{init} / \theta_{ext}$	$\theta_{24} / \theta_{ext}$	$\theta_{48} / \theta_{ext}$	$\theta_{168} / \theta_{ext}$
Yellow-grey earth	9	0.60	0.99	0.89	0.67
	9	0.56	0.99	0.72	0.77
	12	0.57	0.94	0.89	
	12	0.80	0.94	0.90	
	15	0.55	0.99	0.93	0.84
	15	0.92	0.94	0.93	
Yellow-brown stony	3	0.67	0.81	0.80	0.74
	3	0.71	0.87	0.92[*1]	0.97[*1]
	13	0.37	0.81	0.71	0.64
	13	0.55	0.94	0.79	0.77
Gley	14	0.91	0.97	0.97	0.83
	14	0.97	0.98	0.97	
Recent-well drained	1	0.58	0.86		
	2	0.65	0.93	0.99[*2]	0.86
	2	0.64	0.93	0.94	0.83
	10	0.72	0.94	0.91	0.79
	11	0.62	0.96	0.93	0.68
Recent-poorly drained	4	0.64	0.88	0.85	0.95[*1]
	4	0.62	0.87	0.96	0.71
	5	0.89	0.95	0.95	

θ_{init} = initial soil water content
θ_{ext} = maximum soil water content reached as a result of irrigation
θ_{24}, θ_{48}, θ_{168} = soil water content 24, 48 and 168 hours after irrigation
[*1] rainfall increased the soil water content
[*2] borders leaked

The effect of different methods of irrigation on soil moisture and drainage

Different irrigation systems apply water in different ways and the soil moisture response reflects these differences. The border-dyke system applied water at a considerably higher average intensity than all the other systems. The multi-head systems apply water for longer, but at a lower rate (except the 'fixed-pipe' system) than the other spray irrigation systems (Table 6). These differences in application rate are clearly reflected in the rate of change in water content of the top 300 mm of the soil profile (gradient of the 'wetting curve'). For example, flooding by border-dykes results in a very rapid wetting up of the profile and a gradient which is three times steeper than any other irrigation system. Likewise the low intensity but long duration irrigation typical of a multi-head system results in a slow cumulative increase in water content within the upper soil profile (Fig. 5).

Table 6 – Observed response to irrigation categorised by irrigation type

Irrigation type	Soil	Amount of water applied (mm)	Duration of irrigation (min)	Average intensity (mm/hr)	Gradient of 'wetting' curve[1]
Border-dyke	Recent – well drained	75	270	16.7	0.67
		75	270	16.7	0.608
Multi-head	Recent – poorly drained	61	538	6.8	0.044
	Recent – well drained	51	562	5.4	0.065
	Yellow-brown stony	215	1433	9	0.115
		188	1329	8.5	0.042
	Yellow-grey earth	43	1178	2.2	0.01
		55	1403	2.4	0.021
		70	1385	3.1	0.028
		28	736	2.3	0.02
Rotating boom	Recent – well drained	35	342	6.1	0.141
		25	271	5.5	0.194
Spray-gun	Gley	28	226	7.5	0.109
	Recent – poorly drained	21	119	10.6	0.118
		29	110	15.8	0.186
	Recent – well drained	35	251	8.4	0.061
	Yellow-brown stony	21	162	7.8	0.21
		30	151	11.9	0.136
	Yellow-grey earth	57	255	13.4	0.121
		18	127	8.5	0.077

Notes: [1] The rate of wetting of the top 300 mm of the soil profile

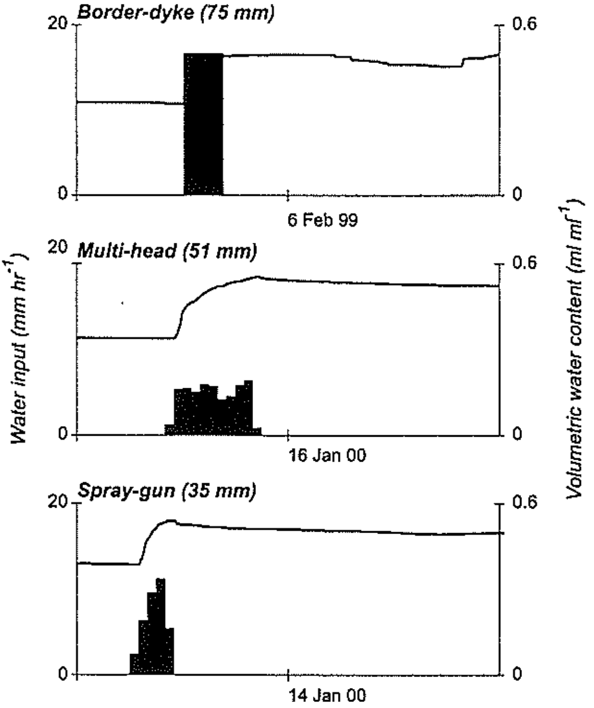

Figure 5 – The soil moisture response (the volumetric water content at 100 mm depth) of Recent-well drained soil to various methods of irrigation. The rate at which the profile wets under Border-dyke irrigation is nearly an order of magnitude greater than that under multi-head irrigation.

Under spray-gun irrigation the speed of response was rapid for all soil types. However, at most sites rapid drainage also occurred. The largest response at 500 mm, reflecting loss of moisture from the profile, was in the Yellow-brown stony and Recent-poorly drained soils. In these soils the high intensity of application induced macropore flow. The other soils are more likely to hold the water in the smaller pores. The length of time the soil water content remained elevated following irrigation varied considerably; however, it was least in the Yellow-brown stony soils (Fig. 6).

This difference in application rate is also significant in terms of how the water is transmitted through the profile. Rapid addition of water has the potential to lead to macropore flow where water is "piped" through the larger pores, for example cracks and worm burrows, without wetting the soil matrix. During the border-dyke irrigation there was clear evidence of this processes from the entrapped air bubbling through the ponded water on the surface.

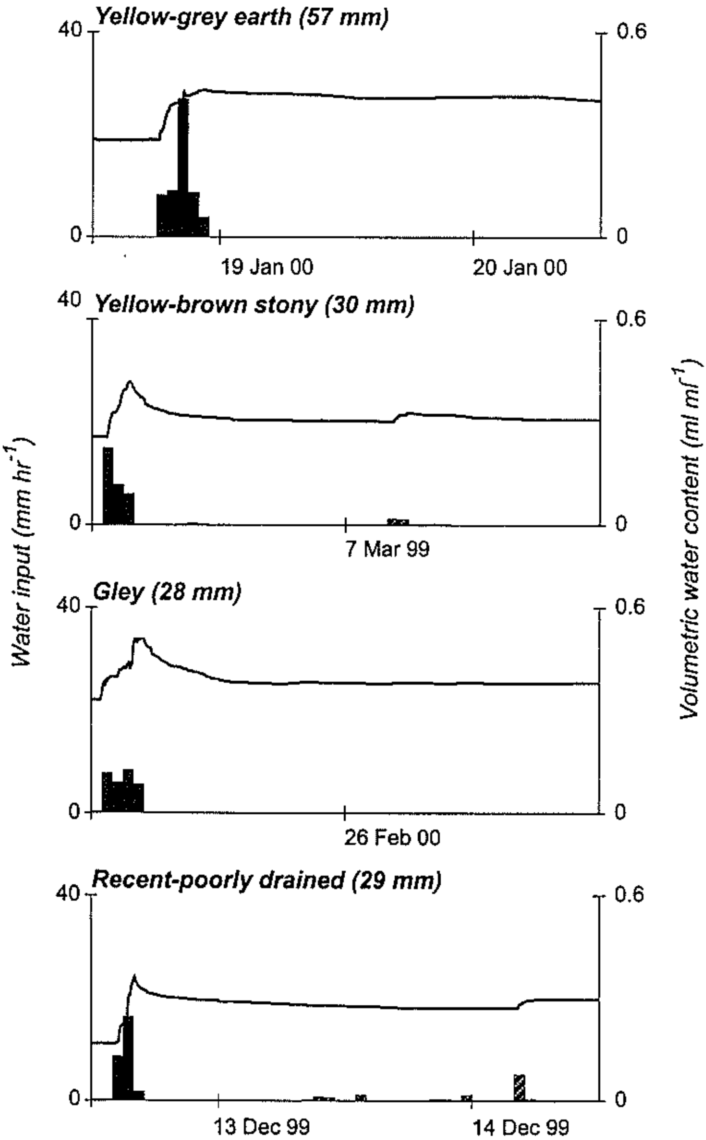

Figure 6 – The soil moisture response (the integrated volumetric water content of the top 300 mm of the soil) of the various soil groups to spray-gun irrigation. The different responses are related to soil physical properties.

For Yellow-grey earths the differences resulting from irrigation technique are less noticeable. This is because this soil has the capacity to store large amounts of water no matter how it is applied. Thus while the spray-gun irrigator is inappropriate for irrigation on Yellow-brown stony soils, it may be appropriate on the Yellow-grey earths (Figs. 6 and 7).

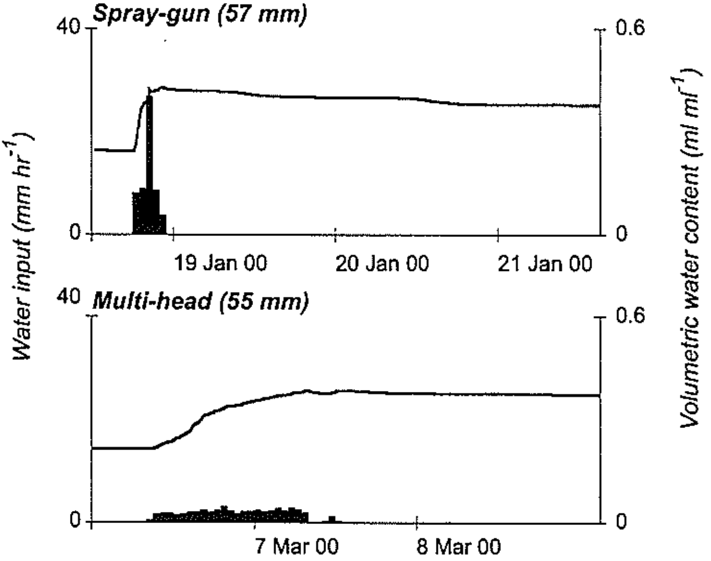

Figure 7 – The soil moisture response (the volumetric water content at 100 mm depth) of Yellow-grey earth to various types of irrigation. The rate at which the profile wets under the spray-gun is five times greater than that under multi-head irrigation. Because this soil can store and hold a lot of water it drains only slowly.

It is also possible to compare how different soils responded to the same irrigation technique (Fig. 6). The low-intensity application of water under multi-head irrigation, combined with the fine-grained nature of the Yellow-grey earth and Recent-well drained soils, results in a slow increase in soil water content. In contrast the Yellow-brown stony soil wets up rapidly. The greatest influence of the different soil properties is in the drainage curves after irrigation. The Yellow-brown stony soils dry quickly compared to the Yellow-grey earth and Recent-well drained soils. Under spray-gun irrigation the differences in response caused by the soil properties are again evident.

With the rapid application of 57 mm of water the Yellow-grey earth wets up quickly and there is very little change in soil water content over the following 2 days. Rapid drainage from the Gley and Yellow-brown stony soils means that 2 days after irrigation the soil water content has declined to almost the initial soil water content. The Recent-poorly drained soil wets up at a similar rate to the Gley and Yellow-brown stony soils; however, it drains at a rate that is between the rates of these soils and the Yellow-grey earths (Fig. 6).

Determining water needs

The amount of irrigation water needed to avoid crop-water stress is a function of the crop type, the amount of moisture in storage, and the hydraulic properties of the soil. However, 'water need' is not only a question of the *amount* of water required, but also *how often* water is required. Since the soils of the Wairarapa store and transmit water at different capacities and rates, both the amount of water required and how often it is needed differ between the soil groups (Hawke *et al.*, 2000b). The distribution of soil groups with respect to the spatial distribution of effective precipitation complicates the assessment of 'water needs'.

The total porosity of a soil determines the amount of space that is available to store water. However, the size of the individual pores, which determine the tensions at which water is held, is more important than their combined volume. Therefore, the moisture retention curves give an indication of the amount of water which can be stored in the root zone at tensions available to plants (Hawke *et al.*, 2000b; Scotter and Clothier, 1986). Soils that can hold only a small amount of plant-available water, such as Recent-poorly drained and Yellow-brown stony soils, need only a small amount of water input before field capacity is exceeded. This results in water flowing, under the influence of gravity, through macropores, wasting water and potentially leaching nutrients from the soil.

The amount of water that is needed to avoid crop stress is also a function of antecedent soil moisture. This is important because the moisture range over which water is plant-available occurs at different moisture contents for each soil group. Irrigation water is needed before the soil moisture conditions fall below the critical level for a given crop-soil combination and cause crop moisture stress. Since the depth of the root zone, and the 'acceptable' level of soil moisture depletion, varies with crop type, soil properties cannot be used in isolation to predict crop water needs. However, water requirements are strongly related to soil hydraulic properties. When the soils are very dry more water needs to be applied to the Yellow-grey earths for soil moisture to become plant-available than for other soil groups. The least amount of water is needed by the Yellow-brown stony soils, if the initial soil moisture content is low. Thus, there is a strong correlation between when water needs to be applied and the characteristics of the particular soil groups. Therefore water needs to be applied more often on soils with a low available moisture capacity, such as Yellow-brown stony soils.

The amount of irrigation water required is dependent not only on these factors, but also on the naturally available water (the effective precipitation). Effective precipitation varies over the Wairarapa, with most of the area experiencing a moisture deficit during the summer (Hawke *et al.*, 2000a). The magnitude of this deficit varies, but most of the Wairarapa plains have an effective precipitation of between -100 and -200 mm, with the deficit in some areas exceeding 200 mm. Because of the importance of soil hydraulic properties, the soil classification scheme can be overlaid on the effective precipitation map to identify the likely deficit associated with each soil group.

Of the area where the soils were classified, 62% have a summer deficit of between 100 mm and 200 mm and 85% of this area was composed of Yellow-grey earths, Yellow-brown stony, and Recent soils (Table 7). Within the twelve possible combinations of summer effective precipitation and soil group there is considerable variability. For example, of the area with a deficit of between 150 and 200 mm, over half is Yellow-grey earths. Of the area with a 0 to 50 mm deficit, 50% is Yellow-brown stony soil and only 5% is Yellow-grey earths. Of the area classified as Recent-well drained, 60% is in deficit by over 100 mm. That is, Yellow-grey earths and Recent-poorly drained soils dominate the areas with the highest summer deficit, while Yellow-brown stony soils dominate the areas with a deficit of less than 100 mm. These differences, variations in soil hydraulic properties, and the variable manner in which soils respond to different irrigation methods, results in different optimal irrigation amounts, application techniques, and timing. Because of the small available moisture capacity and rapid transmission of water through the root zone, the area with Yellow-brown stony soil and high summer deficits is particularly sensitive, and requires careful water management.

Table 7 – The percentage of the classified area in particular summer effective precipitation categories and soil groups

Mean summer effective precipitation (mm)	Soil Group					
	Yellow-grey earth	Yellow-brown stony	Recent-well drained	Recent-poorly drained	Other	Total
< -200	2.38	0.81	1.18	0.43	0.05	4.85
-199 to - 100	28.7	7.70	8.74	9.98	9.18	64.3
-100 to 0	3.58	12.5	4.73	3.66	6.33	30.8

There is no one established criterion for assessing the effectiveness of irrigation (Lincoln Environmental, 1996; Merriam *et al.*, 1999; Painter and Carran, 1978). Therefore, the effectiveness was evaluated in terms of the irrigation scheme's ability to elevate soil moisture to the 'plant available' range for the longest possible time for the least amount of water (Lincoln Environmental, 2000b). The observed irrigation methods all elevated soil moisture above the critical moisture content for pasture, but the length of time soil moisture remained in the available range varied. On the Recent-well drained soil, border-dyke, multi-head, spray-gun, and rotating boom irrigation all caused soil moisture to be elevated for about the same length of time, even though the border-dyke method used twice as much water. Spray-gun irrigation was more effective in elevating soil moisture above the critical level for pasture on Recent-poorly drained and Yellow-grey earths than on the Yellow-brown stony soil. On this latter soil type, rapid drainage means that most of the irrigation water was 'lost' within 6 hours, whereas on the Yellow-grey earth irrigation helps to maintain soil moisture in the 'available range' for 12 - 13 days.

With all irrigation methods some wastage of water, i.e. drainage of water from the base of the root zone of grass, occurred. However, the extent of this wastage varied. Water-use efficiency can be low either because of macropore flow through the root zone under high-intensity application, or because of the low storage capacity of the soil. Thus improving irrigation water use efficiency in the Wairarapa needs to consider irrigation type, the depth of water applied, the intensity of application, and the water storage and transmission properties of the soil.

There is no one 'ideal' irrigation method that will suit the entire area. Spray irrigation is often suitable for pasture; however, the application intensity and the depth applied should take into account the soil's capacity to store water and transmission rates. In general, lower intensity spray methods will be more successful, particularly on soils with high hydraulic conductivity such as the Yellow-brown stony soil. It must be noted that the results from this study are only concerned with water use once the water arrives at the ground surface. The broader question of irrigation efficiency includes the issues of the cost of obtaining water, wastage between the water source (e.g. bore) and the water arriving at the ground surface, and the effect application rate may have on grass growth.

Conclusions

Since most areas of the Wairarapa experience moisture deficit during the growing season, careful and effective water management is critical. The hydraulic properties of the soils vary significantly over the Wairarapa plains.

The nine soil groups identified were found to have considerably different plant-available water capacity and hydraulic conductivity. A considerable percentage of the area most in deficit is Yellow-grey earths, which have a high water holding capacity and a range of appropriate irrigation methods. However, a large percentage of this area also has soil types which are less flexible in terms of the amount of water applied and the appropriate irrigation method. In particular, areas of Yellow-brown stony soil with a high effective precipitation deficit in summer require careful water management.

Water requirements are related strongly to the soil hydraulic characteristics. Soils with a low-capacity to store plant-available water and rapid soil water transmission characteristics, such as the Yellow-brown stony soil, require small amounts of water often. Soils with a larger storage capacity and slow hydraulic conductivity, such as Yellow-grey earth and Recent-well drained, need water less often, and more water can be applied.

In terms of irrigation efficiency, the multi-head systems cause less wastage at all sites; however, too much water was often applied with these systems. The application of a greater amount of water did not equate to increased duration of plant-water availability. In addition, water was often applied before it was actually needed. Therefore the soil hydraulic properties can be used to determine the suitability of irrigation methods, although other factors such as topography and crop type also need to be considered. The most appropriate irrigation method therefore varies across the Wairarapa. In general, the current allocation of 35 mm/week is higher than needed. In many areas water was required only every 10-14 days, and applications of 70 mm every two weeks (the allocation amount) leads to considerable wastage.

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