Improving irrigation management on hillslope pastures

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Abstract

Improving irrigation management in hillslope catchments to mitigate water and nutrient losses requires a good understanding of soil hydrology. A field trial was set up in a small catchment on a centre-pivot irrigated dairy farm in South Canterbury. Runoff was monitored over two irrigation seasons across a hillslope and at the catchment outlet. Seasonal rainfall variability influenced the starting date, frequency and amount of irrigation applied. Nearly 40% of the runoff events in the second season were directly linked to irrigation. The APSIM model was used to investigate the effects of irrigation management on runoff and pasture production. Simulations suggested that changing irrigation could increase pasture yield by 10%, but led to potentially greater runoff. Using soil moisture to control irrigation improved performance, although the location of monitoring within the landscape was important. Using frequent and smaller application depths resulted in yield increase and less runoff. Simulation of variable rate irrigation did not produce further gains. The best approach to reduce overall runoff losses was to maintain a soil moisture deficit after irrigation. The impact of changing irrigation management over the whole farm system in these complex landscapes needs further research.

Keywords: runoff, catchment, modelling, dairy farm

Introduction

The area of irrigated land in Canterbury, New Zealand, has nearly doubled in the last two decades, to approximately 467,000 ha (StatsNZ Tatauranga Aotearoa 2021). One of the main drivers for this change was the fast-growing dairy industry, due to high international demand for dairy products. From 1990 to 2019, the number of dairy cattle increased by 82% in New Zealand (StatsNZ Tatauranga Aotearoa 2021). In the Canterbury region, cow numbers increased from 112,999 to 1,099,567, representing a remarkable increase of 973% in the last 30 years (StatsNZ Tatauranga Aotearoa 2021). This expansion and intensification has had a large impact on the freshwater quality in New Zealand (Larned *et al.,* 2020; Gray *et al.,* 2021). As part of this expansion, irrigated dairy farming has moved into more marginal areas, such as rolling hills (Houlbrooke *et al.,* 2011). Landscapes with hillslopes are prone to surface and subsurface water runoff (Bircham and Gillingham 1986; Bretherton *et al.,* 2010). There is evidence that irrigating grazed hillslopes with impeded drainage, such as slowly permeable fragipans present in loess sheets in South Canterbury and North Otago, can promote water losses *via* surface runoff (Laurenson *et al.,* 2018; Langer *et al.,* 2020). However, hydrological understanding of these systems is still limited. Furthermore, surplus runoff can contain agricultural contaminants and sediment that compromise water quality of surrounding surface water bodies.

Previous studies have revealed that on-farm runoff can compromise pasture water use efficiency, leading to loss of nutrients and reduced pasture production. Sheath and Boom (1985) and Gillingham *et al.* (2003) found that differences in pasture growth in different slope positions were related to declining soil moisture and storage. Variability in physical properties in hillslope soil is one of the key drivers for surface runoff. Runoff processes are complex and, in most catchments, different mechanisms can be observed. Common mechanisms for soils containing fragipans (layers with restrictions to water flow and root penetration) are either infiltration excess (IE) when precipitation rate is higher than the soil infiltration rate, or saturation excess (SE) when water storage of the soil is exceeded. Runoff from both IE and SE have been observed in several studies in New Zealand (Adams *et al.,* 2005; Müller *et al.,* 2006), and there is evidence that both mechanisms show dependency on slope position or seasonal changes. Srinivasan *et al.* (2002) found that SE occurred predominantly on the lower portion of hillslopes. Seasonal changes have been especially observed after long dry periods in summer, when the soil surface can develop water repellence (Müller *et al.,* 2006; Leh *et al.,* 2008) which reduces water infiltration significantly, leading to more IE runoff.

Other important factors to consider in grazed hillslope are the effects of animals. Their behaviour is impacted by slope gradient and position and this affects the

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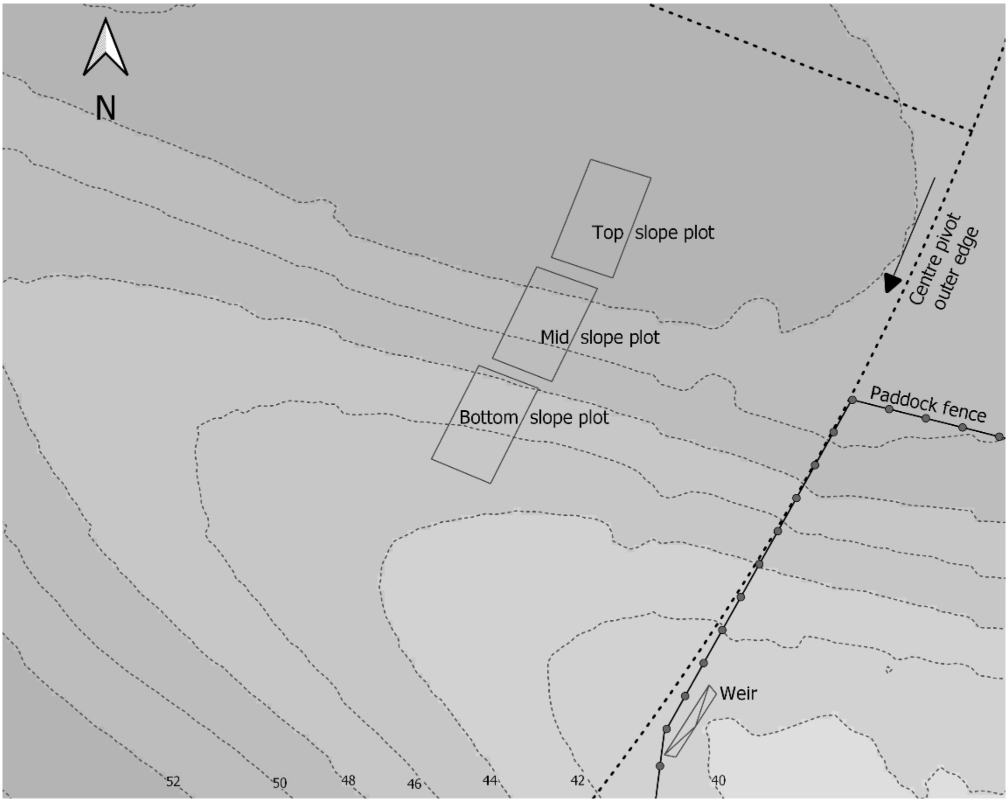

Figure 1 Relief map and schematic of the monitoring site in a South Canterbury dairy farm. The edge of the centre pivot irrigation is marked by the dashed line, with the arrow indicating the direction of movement. The approximate locations of the weir and the three runoff plots installed along the top, middle, and bottom of the south-facing slope are also shown.

distribution of nutrients to the soil *via* excreta (Saggar *et al.,* 1990), as well as soil physical properties due to trampling (Dodd *et al.,* 2016). Understanding the drivers and effects of runoff in hillslopes will lead to improved irrigation practices on farms and the development of strategies for freshwater resource management.

A collaborative research programme was established in 2019 to improve the understanding of the effects of irrigation on runoff losses in the loess rolling hill landscape of South Canterbury. Results from the first year showed that water use efficiency varied for the different slope classes (Langer *et al.*, 2020). This suggested that irrigation management could be improved to ensure a better water supply for plants. Monitoring the site continued, extending the data collection to include the winter period and a second irrigation season. The following study reports and compares data from runoff plots and at catchment level, with the objective to identify the extent to which irrigation and rainfall affected runoff. Based on these measurements, the APSIM model was then used to investigate potential approaches to improve irrigation management for rolling hills. In addition, the merits and problems with a long-term monitoring site and the outlook for future work are discussed.

Materials and Methods

Site and experimental design

In 2019 the experiment site was established at a small catchment located at an irrigated dairy farm in Otaio, South Canterbury (-44.5S, 171.2E). The catchment drained an area of approximately 6.15 ha and was bounded by hillslopes in the North and South, which flattened off towards the headwaters in the West. Water drained into an ephemeral stream in an adjacent forest area. The farmed area was irrigated by a full circle centre-pivot (T-L Irrigation, NE), 340 m long, with rotating sprinklers (Nelson Irrigation, WA) set approximately 6 m apart. The monitoring site was located under the last of the system's six spans (Figure 1).

Soils in the area were characterised as an impermeable fragipan layer overlain by well-drained topsoil, whose thickness varied between 30 cm at the top of the slope to 60 cm at the bottom of the slope. The soils were classified as Fragic Perch-Gley Pallic and Mottled Fragic Pallic according to the New Zealand soil classification (Hewitt 2010). Plant available water capacity (PAWC), defined as the water retained above the fragipan between the matric potential of -1500 kPa and -10 kPa, was estimated at 57 mm, 42 mm and 94 mm for the top, mid, and bottom plots respectively. Detailed soil descriptions are shown in Langer *et al.* (2020).

Catchment surface runoff (Catchment) was measured through a weir at the outflow. The weir was constructed with barriers made of timber (H4 treated 200 mm x 50 mm gauged retaining timber), 8 m and 12.7 m long, installed in January 2019, on both sides of an H-flume device. The water level in the flume was monitored using a laser system (LWL6001-S, NIWA).

To investigate runoff on the hillslope within the catchment (Hillslope), three 40 m^2 runoff plots were installed in September 2019 along the south facing slope, approximately 65 m away from the catchment outflow weir. Langer *et al.* (2020) provides in-depth information on the runoff plot setup and monitoring. The surface-hydrologically isolated plots were positioned at the top (slope angle of 4º), mid (slope angle of 18º) and bottom (slope angle of 15º) of the south facing slope parallel to the tracks of the centre pivot irrigator. Surface runoff was drained into a 100 l collection bin for each individual plot. Precipitation from rainfall and irrigation was monitored using duplicate rain gauges in each plot (6463M, Davis Instruments, US; 0.2 mm per tip). Cows were excluded from the runoff plots with electric fences for the duration of the experiment. The area inside the runoff plots was cut regularly to a height of about 5 cm using a lawn mower. Dry matter yield was determined from two strips (0.47 m wide and 9 m long) for each plot. The grass cuts and fertilizer applications were carried out approximately following the farm's grazing and fertiliser management. After each harvest, 18 kg N/ha were applied in form of urea (Ballance Agri-Nutrients SustaiN®) for the grazing season 2019/2020 and 23 kg N/ha for the grazing season 2020/2021.

Data collection and analyses

Data was collected between 01/09/2019 and 19/04/2021. This period covered two irrigation seasons (01/09/2019 to 19/04/2020 and 01/09/2020 to 19/04/2021; totalling 231 days each) and one winter season (20/04/2020 to 31/08/2020; 133 days). For consistency, monitoring in both irrigation seasons were set to start and end such that the time span was the same, even though, in practice, the timing of the first application differed between years. No irrigation was applied during winter.

Hourly rainfall, temperature, humidity, wind speed and direction, were measured at the NIWA Otaio weather station (no. 43845, cliflo.niwa.co.nz) about 400 m north of the research area. No radiation and potential evapotranspiration (PET) values were available for the period between September 2019 and November 2020 due to equipment failure. For this period, values measured at the Timaru Aero Aws weather station (no. 5086, cliflo.niwa.co.nz) were used, with PET values adjusted ($0.3 + 0.8*PET_{Timaru}$) as the difference between stations, inferred from the period with overlap, was significant. Precipitation measurements for each plot rain gauge were recorded every 10 minutes from October 2019 to September 2020 and every minute from October 2020 onwards. Irrigation was calculated as the difference between the precipitation measured at each plot and the amount of rain measured at the Otaio weather station.

Catchment runoff data were recorded continuously every minute, enabling surface water runoff data to be linked precisely to rain and irrigation events. Surface water runoff at the Hillslope plots was automatically recorded once the volume of water that was collected reached about 35 l (approx. 0.9 mm depth). At this volume, switches triggered a pump sending the water through a flowmeter. Volumes that did not trigger the switches were manually measured during monthly maintenance visits. Because of the lag between runoff initiation and the collection of enough water to trigger the pump, runoff events recorded at the runoff plot level could not always be directly assigned to specific irrigation or rainfall events.

Modelling

Computer modelling was used to complement the analyses of observed data and to investigate how variations in irrigation management were likely to affect pasture production and runoff losses. Simulations were performed using the Agricultural Production Systems Simulator (APSIM) framework, version 7.10 (Holzworth *et al.,* 2014). The simulations were setup with the SoilWat module (Probert *et al.,* 1998) used to describe water movement and solute transport. This module uses the curve number (CN) approach, from the USDA-Soil Conservation Service (SCS 1985; Ponce and Hawkins 1996), to estimate overland runoff. Sub-surface flow was computed based on slope and assumed that lateral hydraulic conductivity was the same as that measured vertically. Soil C and N cycling were described using the SoilN and SurfaceOM modules (Probert *et al.,* 1998). Pasture growth over the different slopes was simulated using AgPasture with a ryegrass/white clover mix, as described in Vogeler and Cichota (2016). Pasture grazing rules were set to mimic the current rotation of the farm (grazing at intervals between 20 and 30 days from mid-August until May, and wintering off farm). To better describe the effects of terrain on pasture growth (*i.e.,* effects of aspect and slope angle), solar radiation values were adjusted based on the methodology described by Allen *et al.* (2006).

For each hillslope, three different areas were simulated, corresponding to the three runoff plots of the field trial. Soil parameters were setup based on measurements and the slope angle of each area (detailed soil descriptions are given in Langer *et al.* (2020)). Values of CN for runoff calculations were gathered from standardised tables (SCS 1985) with minor adjustments based on measurements for the first irrigation season, which resulted in values of 88, 92, and 90 for top, middle and bottom plots. The simulation outputs from the plots were aggregated to the Catchment based on the relative proportion of area in each slope class, rounded to 80% flat (top plot), 5% steep (middle plot), and 15% medium slope (bottom plot), which were determined based on a digital elevation map of the catchment.

Several different irrigation management scenarios, using a centre pivot, were considered (Table 1). The base scenario mimicked the management over the first irrigation season, which was used for validating the model. Another used a fixed irrigation schedule (applying 12 mm every four days, which corresponded to an average ET of 3 mm/day estimated for the summer months at the site), with pauses when rainfall occurred (for 3 days when rainfall surpassed 10 mm over four days). This roughly mimicked a somewhat extreme management that ignored soil moisture entirely. All the remaining scenarios took soil moisture into account to control irrigation, with monitoring site taken to be either the top or the bottom runoff plot (defined as TM and BM). Simple management alternatives were set up to consider different soil moisture levels to trigger irrigations, combined with variations in the irrigation amount applied each time. Three application depths were used, 12 mm, 6 mm and 4 mm, which corresponded to return periods for the irrigator of 3, 2, and 1 day, respectively (marked as HD, LD, and SD). Finally, two scenarios were defined to mimic variable rate irrigation (VRI), attempting to maintain a soil water deficit of 5 mm and 15 mm (identified as D5 and D15). In these scenarios, the irrigator movement was controlled by soil moisture status at the top plot, but application varied for each of the three plots, according to their moisture status, but was limited to zero or between 2 mm and 8 mm (mimicking limitations to control irrigation at low rates and to avoid applying at a too high instantaneous intensity). For all scenarios, irrigation was assumed to occur at an instantaneous intensity of 22 mm/h, which was the average rate for the centre pivot at the location where the runoff plots were installed. Because the amount of application and/or deficit maintained in the soil varied with scenario, the trigger point to start irrigation varied for each management scenario (Table 1).

Table 1 Main characteristics defining the scenarios used to simulate different irrigation management.

Scenario Trigger	Amount applied (mm)	Monitoring site	Return period (days)	(% PAWC)
Fixed schedule	12	none	4	None
HD-TM	12	top	3	30%
HD-BM	12	bottom	3	30%
LD-TM	6	top	2	20%
LD-BM	6	bottom	2	20%
SD-TM	4	top	1	15%
SD_BM	4	bottom	1	15%
VRI-D5	2-8	top, mid, bottom	2	25%
VRI-D15	2-8	top, mid, bottom	2	40%
Validation (base)	3-14	n/a	n/a	n/a

In the scenario description, HD was high application depth (12 mm), LD was low depth (6 mm), and SD was small depth (4 mm); TM was the top plot moisture, BM was bottom plot moisture; VRI was variable rate irrigation, where the soil moisture was returned to either a 5 mm (D5) or 15 mm deficit (D15) post irrigation.

NB. For VRI the irrigation amount varied between 2 mm and 8 mm, depending on soil moisture status of each plot. For the validation run, actual application depths applied on-farm were used and these varied at different dates and even between plots.

Results

Surface runoff measurements

There were differences in the number of recorded Catchment runoff events between the two irrigation seasons. More surface runoff events, 41, were measured during irrigation season 2 at the Catchment level, whereas 31 events were detected in irrigation season 1, and only three over the winter season (Table 2). Despite this, irrigation season 1 had more runoff events triggered by irrigation alone (about 39%) compared to irrigation season 2 (27%). This reflected the fact the

Table 2 Number of runoff events detected at the Catchment level for the three monitored periods and their corresponding distribution according to the type of precipitation to which they were linked.

	Irrigation season 1 (01/09/2019 - 19/04/2020)	Irrigation season 2 (01/09/2020 - 19/04/2021)	Winter season (20/04/2020 - 31/08/2020)
Total surface runoff events	31	41	3
Rain triggered events	10	22	3
Irrigation triggered events	12	11	0
Irrigation and rain triggered events	9	8	0

soil was at greater deficit during irrigation season 1 and the use of less irrigation by the farmer in irrigation season 2. The three runoff events in winter were linked to events in which rainfall totalled 9.4 mm and 8.8 mm over 4 and 2 days consecutively, and one day with 7.4 mm of rain. During the winter period, rainfall was considerably lower than normal, only 55 mm compared to the historical mean of 206 mm (1973-2019, cliflo.niwa.co.nz).

In agreement with the number of events per season, the total amount of surface runoff was larger in irrigation season 2 (Table 3). This reflected about 100 mm more rainfall compared to season 1, as well as variations in rainfall intensity. During irrigation season 1 a total of 83 days with rain were counted with only 56 days during irrigation season 2. Irrigation started much earlier in season 2, following a dry winter the first application was on the 1st of September 2020, whereas the first irrigation in season 1 was on the 29th of October 2019. Nonetheless, about 60 mm more water was applied during irrigation season 1 (Table 3). In total, 34 events were counted during irrigation season 1, with an average of 8 mm and a maximum of 23.7 mm. Only 27 irrigation events, with an average of 7 mm and a maximum of 13 mm, were measured during irrigation season 2. Irrigation measured at the Hillslope level revealed that more water was applied on the bottom slope compared to the mid and top slopes in both seasons (Table 3). About 60 mm more water was applied on the bottom slope compared to the mid and top slopes during irrigation season 1 and about 20 mm during season 2.

The measured runoff amounts at the Catchment level was approximately five times greater in the second irrigation season compared to the first (Table 3). However, the difference between irrigation seasons was much smaller for the runoff measured in the plots. The largest amount of surface runoff at a Hillslope level were measured at the bottom slope and the lowest amount at the top slope consistently for both irrigation seasons (Table 3). There was only slightly more runoff measured for all plots in irrigation season 2, which likely reflected changes in the soil and grass cover following the exclusion of cows at the start of the first season. The amount of irrigation varied depending on the slope position in both seasons. As shown in Table 3, more irrigation was applied at the bottom of the slope compared to the mid and top of the slope. In total, 1% of the total precipitation was discharged as surface runoff for the whole catchment during the first and 5% during the second irrigation season.

Model scenarios

The APSIM model simulated the general trends measured on the monitoring site reasonably well. Calculated cumulative runoff amounts agreed well with measurements (Figure 2A), while pasture growth was only slightly underestimated, but the relative differences between plots was well captured (Figure 2B). Only values for the first year are shown and discussed, because there were considerable changes over time in the grass and soil surface of the runoff plots. The

Table 3 Summary of water balance components measured at a dairy farm in South Canterbury over two irrigation seasons and the winter period in between. Values are given for the whole catchment (6.1 ha) and for three runoff plots installed at three locations along the south facing slope of the catchment. Irrigation seasons were defined between 1st September and 19th April for both years and the remainder winter season of 2020.

Location	Season	PET (mm)	Rain (mm)	Irrigation (mm)	Surface runoff (mm)
Catchment	Irrigation season 1	629.8	362.0	250.9	6.2
	Irrigation season 2	616.2	428.1	189.5	32.3
	Winter season	121.3	53.6	0.0	0.1
Top slope	Irrigation season 1	629.8	360.2	236.2	13.2
	Irrigation season 2	616.2	428.1	177.8	15.4
	Winter season	121.3	55.4	0.0	3.6
Mid slope	Irrigation season 1	629.8	360.2	226.6	35.7
	Irrigation season 2	616.2	428.1	185.3	47.7
	Winter season	121.3	55.4	0.0	4.2
Bottom slope	Irrigation season 1	629.8	360.2	290.0	46.5
	Irrigation season 2	616.2	428.1	205.4	50.6
	Winter season	121.3	55.4	0.0	6.8

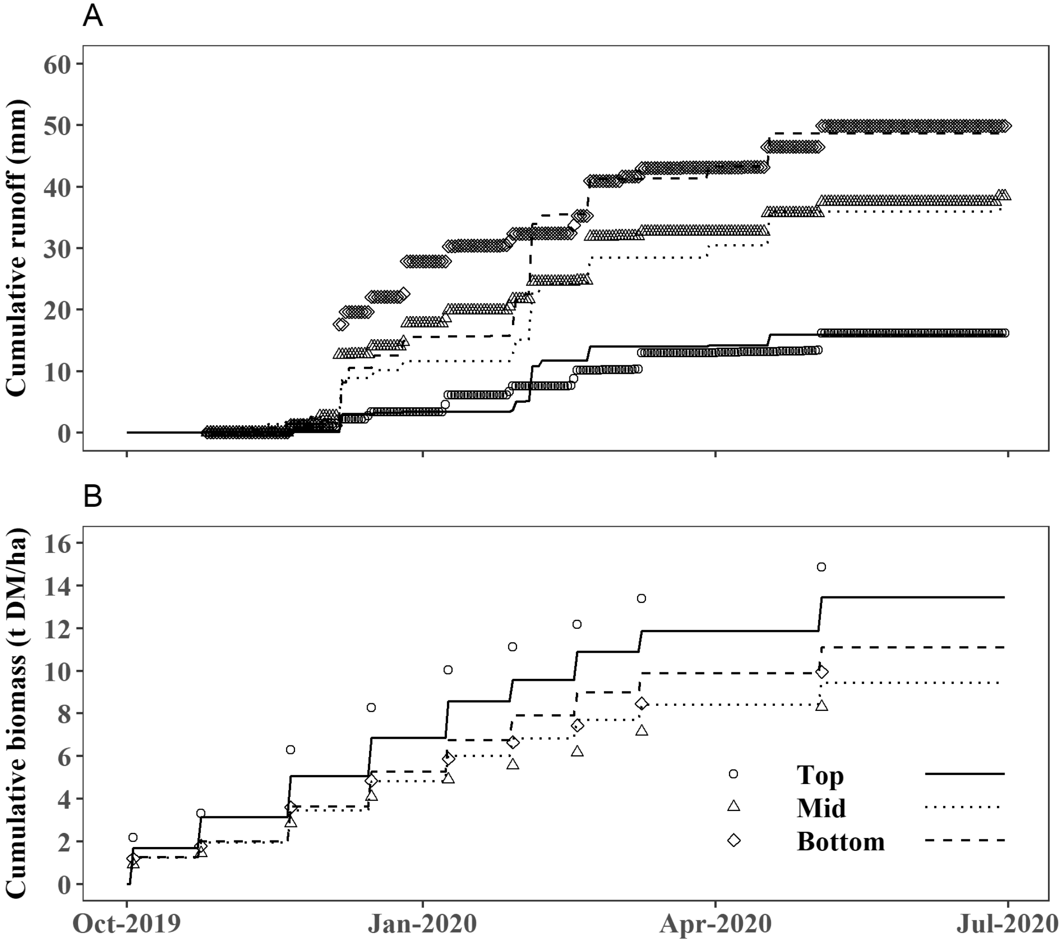

Figure 2 Observed (symbols) and predicted (lines) cumulative amount of runoff (A) and harvested biomass (B) for three runoff plots installed along the top, middle, and bottom of a slope in a South Canterbury dairy farm.

sward was in much better state, with higher and more homogenous plant cover. To obtain good agreement for simulations for the second season, soil parameters had to be changed to reflect non-grazed conditions (lower CN for runoff and more uniform distribution of nutrients across the slope). As this did not reflect the overall paddock and catchment area, it was postulated that only the first irrigation season represented the general conditions of the paddocks under grazing.

The summary of results using the APSIM model to simulate various scenarios for irrigation management are shown in Table 4. All simulations suggested that the site was under-irrigated in general, with more water being used compared to the validation run, which was amount measured on the farm. All simulations produced more pasture than the validation run. However, the measured amount applied in the plot at the bottom of the slope (218 mm) was larger than several other scenarios, which had higher estimated yields. This suggested that that the plot was slightly over-irrigated, or that the timing of irrigation was not right.

Fixed schedule irrigation used the largest amount of water, more than twice the validation, representing almost 25% less water use efficiency (WUE, kg, DM/mm water), and with the highest amount of runoff being three and a half times the validation run.

The results from the other scenarios, that used soil moisture to control irrigation, clearly showed that using the top plot to monitor water deficit resulted in more irrigation being applied which achieved higher yields. This reflected the fact that the flat areas represented most of the catchment area, and, thus, management tailored to these areas was likely to have the greatest impact on WUE. However, such management always resulted in considerably more runoff losses than the scenarios where soil moisture at the bottom plot was used to trigger irrigations. There was a clear trend for less runoff, especially as a proportion of irrigation, when less irrigation depth was applied.

The scenarios using VRI produced results that were quite similar to those when irrigation was triggered by soil moisture (Table 4). This suggested that further gains in WUE or reduction in runoff are limited. Considerable reductions in losses in the VRI scenarios was estimated for the mid plot only (data not shown), which had the steeper gradient, but represented only a small proportion of the total area. Maintaining a larger soil water deficit limited runoff with no pasture yield penalties.

Discussion

There were large differences in runoff responses across the hillslope and from the catchment between the irrigation seasons and winter. Rainfall variability and irrigation inputs were both important factors. In both irrigation seasons, disproportionally more surface runoff was generated at the catchment and plot level, compared to the winter season. Such a large difference may have been atypical, given that average winter rainfall is normally four times greater than recorded at the site. A more typical rainfall pattern would cause wetter soil conditions, generating more SE runoff due to rainfall exceeding plant uptake. With such an exceptionally dry winter, and PET of about 120 mm, there was a relatively large soil water deficit at the start of the second irrigation season. This led to earlier irrigation application dates in season 2 compared to season 1.

Irrigation was directly responsible for a large proportion (27-39%) of the Catchment runoff events depending on the season, although the majority was directly related to rainfall alone. In particular, it was noted that substantial surface runoff was mostly linked to large rainfall events in the second irrigation season. This finding was consistent with findings by Buda *et al.* (2009) and McDowell *et al.* (2006), which showed that the generation of surface runoff events were linked to higher rainfall intensities. Indirectly, irrigation may be expected to contribute to rainfall-driven events, as it maintains soil water content closer to saturation levels.

The variability in timing and amounts of rainfall required different irrigation management responses. The farmer adapted his irrigation schedule somewhat based on soil moisture monitoring. Overall, more irrigation was required in the drier season 1 to keep up with the plant demand. While irrigation needed to be applied earlier in season 2, less water was applied over the course of the whole season. In contrast, during irrigation season 1, the majority of irrigation water was applied later in the season. The farmer's response to the variable rainfall supported the importance of using soil moisture measurements to schedule irrigation, although, to be effective, this should be supported by good soil water balance.

Although not quantified in this study, soil hydrophobicity (or soil water repellence) is a key factor in increased risk of runoff from hillslope pasture. Hydrophobicity can induce runoff through IE, as the soil's capacity to absorb water is reduced considerably (Müller *et al.,* 2016; Bretherton *et al.,* 2018). Often hydrophobicity develops after prolonged dry periods. This can be expected to occur on irrigated pastures during periods where plant water use exceeds irrigation supply, leading to soil water deficits. Consequently, it is expected that hydrophobic responses of soil to irrigation will vary over the season. For example, rapid

Table 4 Summary from simulations of different scenarios with varying irrigation management.

Scenario	**Irrigation** (mm)	(%)	**Pasture production** (t DM/ha)	(%)	**Runoff** (mm)	(%)	**WUE** (kg/mm)	(%)
Schedule	348.0	102.2	14.0	8.9	94.7	258.6	23.8	-23.7
HD-TM	252.0	46.4	14.0	9.2	45.3	71.3	28.6	-8.6
HD-BM	192.0	11.6	13.8	7.1	22.9	-13.4	31.9	2.2
LD-TM	246.0	43.0	14.8	15.2	38.7	46.4	30.5	-2.3
LD-BM	204.0	18.5	13.9	8.0	24.3	-8.2	31.3	0.2
SD-TM	264.0	53.4	14.1	9.5	40.1	51.6	27.9	-10.5
SD-BM	216.0	25.5	14.0	8.8	26.3	-0.6	30.7	-1.7
VRI-D5	244.8	42.2	14.0	9.3	36.2	36.9	29.0	-7.1
VRI-D15	215.4	25.2	13.9	8.4	26.3	-0.4	30.6	-1.9
Validation (base)	172.1	-	12.8	-	26.4	-	31.2	-

Values shown are an aggregation of simulated results based on the proportion of area for the three slope classes, corresponding to the runoff plots of the monitoring site, representing the 2019-2020 irrigation seasons. Relative differences (%) of each option to the validation (base) scenario. WUE is water use efficiency, HD is high application depth (12 mm), LD is low depth (6 mm), and SD is small depth (4 mm); TM signifies top plot moisture, BM is bottom plot moisture; VRI is variable rate irrigation, maintaining either a 5 mm deficit (D5) or 15 mm deficit (D15) post irrigation.

soil drying over dry summer periods might lead to hydrophobic conditions, increasing the risk of IE when irrigation is applied.

While the amount of Catchment runoff over the irrigation season 2 was more than five times that of season one, the recorded runoff at plot level was only approximately 20% larger in season 2. In general, the relationship between surface runoff at the catchment and that measured at the plots was quite weak, and deviations were larger in irrigation season 2. This highlighted the differences in methods and scale, but was most likely a reflection of the impact that grazing cattle can have on soil surface conditions. Whilst most of the catchment area was grazed, the runoff plots had been fenced off for more than 1.5 years and it was noticeable that the ground cover changed over time. With no trampling damage, grass cover was much more uniform in the runoff plots. Reductions in soil macroporosity and saturated hydraulic conductivity can result from animal trampling (Gray *et al.,* 2021), leading to conditions that promote surface runoff. The use of runoff plots provided valuable information to understand differences between locations and slopes. However, care must be taken when employing this methodology over long periods of time, as changes in surface conditions within the plots may not represent the overall condition of the catchment where grazing takes place. This breaks the hydrological flow across the landscape and does not capture the effect it may have on subsequent runoff.

Modelling was useful in exploring how irrigation management could be improved. One of the key findings was that there was likely to be an opportunity to increase DM production, albeit a small one. All simulated scenarios showed greater yields, although this was due to applying more water *via* irrigation. Several of the scenarios showed that runoff could be reduced compared to the base scenario. However, the scenarios where pasture production was maximised had increased runoff losses. For example, triggering irrigation based on soil moisture monitored at the top plot, which represented most of the flat areas, resulted in greater gains in production. But this scenario tended to generate greater runoff, due to steeper areas being generally over-irrigated. A compromise between increasing production and maintaining low levels of runoff is needed. As expected, applying low irrigation rates more often resulted in better outcomes. Maintaining soil deficit after irrigation resulted in better water usage and this practice tend to minimise runoff due to SE. It was important to note that this modelling exercise did not include the potential effects of water repellence by dry soil. Maintaining water deficit over the summer may induce surface hydrophobicity countering its benefits due to induced runoff via IE. This requires further study.

Despite the large variability in runoff and soil conditions observed for the hillslope plots, the catchment modelling VRI scenario did not improve production or reduce runoff better than some of the scenarios that simply used soil moisture to control irrigation (Table 4). While this may be surprising, it was a function of the relatively small area occupied by the slopes, with approximately 80% as flat land. This was a function of the differences in soil water balances on the slopes and was subject to large variability in rainfall that was difficult to predict. While VRI may be optimised further to improve production and reduce runoff, it is questionable how practicably this could be done in the field, or how to justify it economically. It is important to note that the current analysis of VRI used a relatively simple modelling setup and a more thorough investigation may show conditions in which it becomes a viable option.

The complexity and variability of hydrological conditions, as described by Langer *et al.* (2020) was reflected in the variation of generated surplus runoff at the different plot positions. The data collected from the monitoring sites contributed to the understanding of the hydrology in this challenging landscape, but further work is needed. Drainage was assumed to be low, due to the nature of the loess-derived soils (Webb and Burgham 1997), but sub-surface flow may have been significant, which would account for water losses in such catchments.

Understanding the various pathways for water loss is important to determine the risk of correlated environmental impacts such as sediment and nutrient losses. Changes in irrigation management, such as the scenarios modelled in this work, will have an impact on environmental outcomes. Increasing pasture production allows for increased stocking rates and, if runoff occurs (or increases as was predicted in some scenarios), sediment and nutrient losses will increase. Future analyses should consider the implications of changing irrigation practices on the whole farm to assess environmental risks.

Conclusions

The trial confirmed that irrigation triggers a considerable number of runoff events and that good management is important to avoid water losses, even though the total loss as surface runoff at the catchment level seemed relatively small. Large variation between seasons was observed, with greater runoff in the second year, but this was linked to large rainfall events. Modelling was a useful tool to explore irrigation management and trade-offs between pasture production and runoff, and understand where soil moisture should be measured in variable landscapes. Using the APSIM model enabled simulation of the conditions of the first irrigation season well. Based on this, scenarios using different irrigation management showed that using soil moisture monitoring improved pasture production, without increasing runoff losses. Using VRI did not considerably improve the performance of irrigation. The use of small application depths and maintaining a deficit after irrigation provided the best results. Further research is needed to understand the implications of changing irrigation management over the whole farm and its environmental impact.

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