The behaviour of sheep around a hill country stream and impacts on freshwater quality.

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Science

In

Animal Science

School of Agriculture and Environment

Massey University

Palmerston North

Charlie Barnes

2021

Abstract

Recent amendments by the New Zealand Government to the Resource Management Act (RMA) regulations proposed that fencing and a 3m setback were required for streams more than 1 m wide and the exclusion of farmed cattle, deer and pigs from these waterways (Ministry for the Enviornment, 2020). Currently, sheep are not required to be excluded from waterways. Furthermore, there is no literature on the behaviour of sheep in New Zealand around hill country streams or their impacts on water quality.

During the Summer of 2021 (February), a crossover design trial was conducted with forty mixed aged ewes in a hill country paddock transected by a fifth order stream on Massey University's Tuapaka farm. During the study, ewes had access to a trough for the first week and did not have access to the trough on the second week. Ewes were monitored using motion activated cameras, accelerometers attached to a halter, and GPS units attached to a collar. Water sampling was conducted for two days of each week during each treatment and analysed for suspended sediment, total phosphorus, dissolved phosphorus, total nitrogen, ammonia, nitrate, and *E. Coli*. The results from the summer trial showed that the behaviour of sheep around the stream was not influenced by the availability of a drinking trough. When sheep had no access to the trough, however, they spent more time within areas of the stream that were easy to access and were observed to drink from the stream. Total phosphorus concentration was lower in the first week (unrestricted access to the trough, $p = 0.020$) were as suspended sediment, total nitrogen, and *E. Coli* loads ($p = 0.0002$, 0.0374 and 0.029 respectively) were higher compared to the second week (restricted access to the trough). There were no recorded instances were sheep defecated into the stream and two occurrences of urination near the stream. This study suggests that sheep had a minimal influence on water quality and any effects were likely due to rainfall events.

A follow-up trial following the same methodology was conducted in Autumn (April) within the same paddock and with the same sheep. The behaviour of sheep around the stream during Autumn was not influenced by the availability of a drinking trough. Access to the trough had an inconsequential impact on the behaviour of the ewes within the stream zone. It is probable that the moisture content of the pasture was sufficient to satisfy the water requirements of the sheep during the trial and negated the need to drink from the stream. Indicators of water quality were elevated during and immediately after rainfall events and highlights the sediment loss that can occur from a grazed pasture during a rainfall event. There was no association between sheep activity and a decline in water quality. Suspended sediment loads were greater when during the first week (restricted trough access, $p = 0.002$) whereas

total nitrogen, total phosphorus and *E. Coli* loads did not differ between treatments (p = 0.629, 0.989 and 0.528 respectively) There were no recorded instances were sheep defecated into the stream.

These experiments showed that sheep interaction with a natural waterway during summer and autumn on a Manawatu Hill country farm had an insignificant influence on the water quality metrics measured. Therefore, it is unlikely that excluding sheep from accessing natural waterways would result in improvements to water quality.

Acknowledgements

I would like to thank the sponsors of this research for providing financial assistance to help me successfully complete this research. I could not have done this without you.

C Alma Baker Trust

Sinclair Cummings Veterinary and Animal Science

Tilt Renewables Research Bursary

At the beginning of the year, I was naïve to the enormity of the task that writing a thesis involved. It has been the biggest challenge of my life so far and getting to this stage has involved many headaches, long nights, early starts and more coffee than I think is safe to drink. I would not change it for the world.

I am very grateful to be where I am today, having learnt what I have learnt, and been exposed to many experiences that have changed me. I could not be more thankful for my supervising team, Rene, Ina and Lucy. They have been pillars of guidance and support throughout a tumultuous year, always showing patience and always steering me back in the right direction. At times I thought I was too far down the rabbit hole, and some of the writing I submitted for feedback, on reflection must have been a bit of a laugh. I have thoroughly enjoyed my time working with you all. Thank you.

There has been many people and departments along the way that have lent a hand and a thoughtful word. The people that are involved with Massey University are incredible and a credit to the Institute. The Animal Science department has become my home for this year and the colleagues in my office have been exceptional distractions.

My family: Catherine, Peggie, Lucy and Howie have been extremely supportive throughout this adventure. They encouraged me to start this journey and have walked with me along the way. Their support in pursuing self-progression is something I cherish. It is also important to recognise the efforts of the lads, for always having a cold tube ready for a debrief and to aid in the generation of thoughts.

Lastly, I could not have done this without Brooke, Bella, Ashi and Heidi. Your love has created an environment that has pushed me forward and kept me grounded. I would be lost without you. To spend each night listening to me ramble on about sheep and a stream, it must have been riveting. Hopefully the chat will improve with time. I am truly grateful to have you in my life.

Contents

Table of Figures

Chapter 1 Literature Review

1.1 Introduction

This research was conducted with the aim of answering these research questions and providing suitable recommendations to both farmers and policy makers on the role sheep have in the water crisis.

1) How do sheep behave around a New Zealand hill country stream?
2) What impact does accessibility to a reticulated water trough have on sheep behaviour?
3) What are the consequences to stream water quality as a result of sheep having free access to the flowing water?

New Zealand Sheep numbered 26,821,846 in 2019 (Statistics, 2021). This was comprised of approximately 17 million breeding ewes and 10.4 million hoggets, dry ewes and rams (Beef and Lamb, 2020a). National sheep numbers have declined by 15.4% since 2008 (Statistics, 2021).

In New Zealand, hill country landscapes occupy 30% of the total land area and 71% of pastoral land use (McCoard, 2017). Hill country sheep farms in New Zealand often have reduced soil fertility because of climatic extremes and the lithology of the landscapes. They have limited water reticulation due to challenges created by their contour and topography resulting in sheep accessing drinking water primarily from dams and streams or water from streams being pumped up into troughs (Donnison et al., 2004). There is increasing recognition of the tension between livestock production and water use and quality (Julian, Beurs, et al., 2017; Zonderland-Thomassen et al., 2014). The need to exclude stock from waterways and streams to protect water quality and reduce negative impacts on stream banks will add substantial cost in terms of fencing and the installation of reticulated water systems.

In 2019, the New Zealand Government proposed that fencing and a 3m setback were required for streams and drains more than one metre wide (Ministry for the Enviornment, 2020). Changes to stock exclusion in the Resource Management Act (RMA) regulations, required the exclusion of farmed cattle, deer and pigs from waterways more than 1 m wide (Ministry for the Enviornment, 2020). Currently, sheep are not required to be excluded from waterways.

Currently, there is no information available about the behaviour of sheep around natural waterways in New Zealand hill country nor on their impact on water quality. Research has shown that the amount of water contained in pasture during some periods of the year, can meet the water requirements of sheep without negative impacts on performance (Dove et al., 2000), suggesting that sheep may not need to drink from waterways year round. Given the potential high cost of fencing stock from waterways, it is critical that more research is undertaken to determine if sheep interact with and drink from hill country streams and what impact, if any, this has on water quality.

1.2 Water Quality

1.2.1 Water Issues in New Zealand

New Zealand spans from 34 to 47S on the middle latitude of the Southern Hemisphere (Caloiero, 2015; Julian, de Beurs, et al., 2017). New Zealand is comprised of two, long narrow islands with a total surface area of 268,680 km^2, with axial ranges rising up to 3,764 m. Pastoral agriculture is the single largest land use category in New Zealand and occupies about 40% of the nation's total land area (Chibuike et al., 2021; Davies-Colley, 2013; Tozer et al., 2021). Excess nutrients, increased sedimentation and organic pollution in rivers is often attributed to agricultural land use (Julian, Beurs, et al., 2017; Monaghan, Wilcock, et al., 2007; Riseng et al., 2011). Over the past three decades, pasture area is declining whereas fertiliser inputs and livestock densities are increasing (Julian, Beurs, et al., 2017; Martinez et al., 2009; Petry et al., 2002). Impacts of livestock can be further exacerbated by the ongoing intensification of farming due to the addition of excess nutrients and sediment to water (Death et al., 2018; Joy, 2015). Intensified agriculture increases the loss of nutrients in runoff which may have serious public and ecological health implications (Hooda et al., 2000; Withers et al., 2014). Serious ecological impacts linked to agricultural nutrient exports include eutrophication, hazardous algal blooms and hypoxia (Death et al., 2018; Goeller et al., 2019; Riseng et al., 2011).

Water quality is strongly related to land use (Davies-Colley, 2013; Larned et al., 2020; McDowell et al., 2021). Livestock are the dominant source of faecal contamination to New Zealand's freshwaters (Collins et al., 2007; Davies-Colley, 2013). Streams and rivers transport nutrient loads to water bodies downstream. Streams in grazed pastoral landscapes have increased runoff due to lower interception and evapotranspiration of grasses compared with forest, plus reduced infiltration owing to soil compaction by livestock trampling (Davies-Colley, 2013). The increased runoff and lowered infiltration are major drivers of reduced stream water quality. Land area in pastoral use negatively impacts visual water clarity and is positively correlated with nutrient and *E. coli* concentrations in a catchment (Howard-Williams et al., 2010).

One-third of New Zealand's 14.7 million hectares of pastoral land has been identified as grazed hill country (Tozer et al., 2021; van der Weerden et al., 2020). Hill country includes hill and high-country pastoral land where annual pasture dry matter production and stock numbers per hectare are lower than flatland. Sheep and beef cattle graze the majority of hill country pastures (Saggar et al., 2015; Zhong et al., 2016). Overgrazing of hill country may leave soil bare and exposed. Steep slopes that are vegetated by shallow roots and introduced grasses, are susceptible to destabilisation which promotes reductions in visual clarity of waterways through increased mobilisation of sediments (Julian, Beurs, et al., 2017). Soil erosion can be amplified by sheep tracks and hillside scars created for scratching and shelter. Channels created by sheep tracks along hill sides carry soil away into water sources (Wright, 2012). Intensive livestock grazing on steep slopes compared with flatter areas can generate increased amounts of erosion through treading, excreta and surface runoff which increases sediment and nutrient loss (Gillingham & Thorrold, 2000; Julian, Beurs, et al., 2017). The faeces of sheep carry a myriad of bacterial and protozoan pathogens (Alegbeleye & Sant'Ana, 2020). Concentrations of excreta and urine can vary spatially, with deposits often elevated on flatter areas where animals tend to spend more time (Betteridge et al., 2020; Saggar et al., 1990).

The development of land for intensive agriculture has degraded the ecological health and water quality of many rivers and streams in New Zealand (Howard-Williams et al., 2010; McKergow et al., 2016). Agricultural land is a significant contributor of fine sediments, nutrients, and other contaminants in diffuse pollution to waterways (Harrison et al., 2019; Howard-Williams et al., 2010; Julian, Beurs, et al., 2017). With minimal consideration of environmental protection, the state of water quality is a symptom of historical nutrient inputs and management strategies aligned with production goals.

1.2.2 Land Use Classifications

Over the 100 years, land use in New Zealand has changed to match global food demand and land productivity potential (Julian, Beurs, et al., 2017; McDowell et al., 2009). In New Zealand, the process for determining environmental sustainability is defined through the Land Resource Inventory (LRI) and the Land Capability Classification (LUC) systems (Lynn et al., 2009; Manderson, 2003). These are graded, hierarchical scales which consider many potential and existing environmental management factors such as nutrient leaching, nutrient runoff, soil erosion, soil compaction and natural biodiversity that identify increasing limitations as you go from class 1 to 8 (Manderson, 2003).

The New Zealand Land Use Classification scheme (LUC) has two key components. The Land Resource Inventory (LRI) which is compiled as an assessment of physical factors considered to be critical for long-term land use and management. These include rock type, soil type, slope angle, erosion type and severity and vegetation cover. Secondly, the inventory is used for LUC Classification, whereby land is categorised into eight classes according to long term capability to sustain one or more productive uses (Lynn et al., 2009). The primary function of the LUC is a systematic arrangement of different kinds of land according to those properties that determine its capacity for long-term sustained production (Lynn et al., 2009).

Slope Group	Slope angle (degrees)	Description	Examples
A	0-3°	Flat to gently undulating	Flats, terraces
B	4-7°	Undulating	Terraces, fans
C	8-15°	Rolling	Downlands, fans
D	16-20°	Strongly Rolling	Downlands, hill country
E	21-25°	Moderately steep	Hill country
F	26-35°	Steep	Hill country and steeplands
G	>35°	Very Steep	Steeplands, cliffs

Table 1 Slope classification. Adapted from Lynn et al., (2009). Updating and producing the land use capability survey handbook 3rd Edition.

A mosaic of slope classes, with different aspect categories, production potentials and variable responses to added nutrients and excretal inputs dominate New Zealand’s hill landscapes. Hill country covers both the North and South Islands of New Zealand, whereas high country which is defined as land over 700 m altitude is only found in the South Island (Swaffield & Hughey, 2001).

1.2.3 Freshwater quality standards and interventions

In New Zealand, the principal framework for freshwater management is the Resource Management Act 1991 (RMA) (Resource Management Act, 2020). The effects of human activities on the natural and physical resources of New Zealand are managed by the RMA. The RMA is responsible for developing and implementing policy documents (national and regional policies, and regional and local level resource management plans) under a hierarchy of local councils, institutions and ministries at a national and regional level (Rouse & Norton, 2017).

The legislative and policy frameworks aim to improve recognition of indigenous relationships and rights and to promote a community-wide collaborative approach to freshwater management (Booker, 2018). *Te Mana o te Wai* represents the innate relationship between *te hauora o te wai* (the health and mauri of water) and *te hauora o te taiao* (the health and mauri of the environment), and their ability to support each other while sustaining *te hauora o te tāngata* (the health and mauri of the people) (Booker, 2018).

New Zealand's freshwater condition is an issue that regional and national governments have responded to with a range of initiatives both regulatory and non-regulatory to attempt an improvement in water quality (Death et al., 2018). Initially, the Land and Water Forum (2010) recommended clear environmental standards and 'bottom lines' important to human and ecosystem health across a range of water quality attributes. This was then built upon by the New Zealand Government which recently proposed enforceable national river and stream water 'bottom lines' of 1 mg L^{-1} dissolved inorganic nitrogen (DIN) and 0.018 mg L^{-1} dissolved reactive phosphorus (DRP). These environmental standards are not based on ecosystem health and are focused on preventing nitrate toxicity in town drinking supplies by setting a bottom line for dissolved inorganic nitrogen at 2.4 mg L^{-1} (Davis, 2014; McDowell et al., 2021).

The National Policy Statement for Freshwater Management (NPS-FM) has made FEPs mandatory. The farm environment plan (FEP) is a framework for the delivery of advice (Ministry for the Enviornment, 2020). However, McDowell et al. (2021) noted more work is needed to develop robust quality standards and both the capacity and capability of regulators and providers to audit and deliver farm environment plans. Water quality is an absolute concept not related to water composition alone (Davies-Colley, 2013). Improving the definition would need to reference how composition affects suitability-for-use of water, or, more widely, its ability to support water values.

The revised National Policy Statement for Freshwater Management (NPS-FM) in 2020 required the exclusion of farmed cattle, deer and pigs from rivers with a bed more than 1 m wide anywhere within the land parcel (Ministry for the Enviornment, 2020). Developing a national policy to prevent farm animals from entering waterways has the potential to improve freshwater environments. This could enhance recreational opportunities, cultural values and habitat biodiversity, providing benefits to many

New Zealanders within a generation (Tait et al., 2017). Sheep, however, were not included in those regulations.

1.2.4 Water Contaminants

Extensive open pastoral stream habitats have become common within the last century as a result of agricultural development (Champion & Tanner, 2000). As a result, management issues relating to these streams involves enrichment of nutrients from non-point sources. Dissolved nitrogen and phosphorus are perhaps of greatest concern among solutes in rivers, mainly due to these elements being readily available forms of commonly growth-limiting nutrients for aquatic plants including algae (Davies-Colley, 2013; Doehring et al., 2020). Nitrogen is toxic to aquatic life in its ammonia and nitrate forms (Davies-Colley, 2013; Fonte et al., 2012). Nuisance algal growth is influenced by increased availability of P (Jarvie et al., 2013; Withers et al., 2014). In addition, the over-fertilisation of aquatic plants leads to excess plant growth, the depletion of dissolved oxygen in water and algal bloom growths which subsequently can have damaging effects. Contact recreation and water supplies are affected by faecal matter and associated pathogens (Davies-Colley et al., 2018; Howard-Williams et al., 2010).

1.2.4.1 Suspended Sediment

Water quality is influenced by sediment concentrations. At a catchment scale, small farm streams may contribute the majority of the sediment and pollutant load (Monaghan et al., 2021; White et al., 2009). Sediment loads from low order streams (<1m wide, 30cm deep and in flat catchments dominated by pasture) account for an average of 77% of the national load in NZ (73% of total N and 84% for dissolved reactive P) (McDowell et al., 2017). Stream and riparian damage resulting from livestock grazing and trampling includes alterations in watershed hydrology, changes to stream channel morphology, soil compaction and erosion, riparian vegetation destruction, and water quality impairments (Agouridis et al., 2005). The presence of livestock near streams and within the riparian zone can dislodge sediment and increase soil erosion through treading which can develop direct pathways via walking tracks for sediment to enter waterways. Stock exclusion and riparian retirement can reduce bank erosion by 80% (Monaghan et al., 2021). Elevated suspended sediment loads reflect enhanced erosion processes, land instability, and often a loss of productive soils within a catchment (Vale et al., 2016; Walling & Fang, 2003). An elevated surface concentration of nutrients is attributed to a build-up in the immediate vicinity of the stream area as sediment is transported through a waterway (Vought et al., 1994). Important transport sources of sediment mobilisation into waterways involve overland flow, sheet erosion and rill erosion (Bargh, 1977; Greenwood & Zhang, 2020). Erosion adversely affects soil fertility and productivity by reducing organic matter, nutrients, soil biota, infiltration rates, water holding capacity and soil depth (Jones et al., 2008). Sediment impacts occur where eroded soils enter a waterway and settles or is redistributed further downstream (Jones et al., 2008; Jones et al., 2012; Walling & Fang, 2003). A result of elevated sediment loads may include an increase in the severity of floods, a reduction in the clarity and quality of water, a degradation of stream biology, aggradation of the stream bed and increased sedimentation over the stream bank.

Groups of sediment can be defined by categories of special particles such as E. coli, suspended particulate matter such as organic carbon and nutrient content or reflective particles that influence visual clarity and turbidity (an index of light side-scattering) of water (Davies-Colley & Hughes, 2020; Gall et al., 2019). Sediment can damage aquatic life both by restricting sunlight penetration and depositing courser material on bed sediment (Davies-Colley & Hughes, 2020; Gall et al., 2019). This influences plant and algae growth and diversity and the ability of some aquatic species ability to see. A reduction in channel capacity as a result of the deposition of sediment increases the risk of flood severity (Jones et al., 2008; Lane et al., 2007). Reduction in water quality and clarity may occur as a result of in increased water temperature from shallower channels and increased turbidity as a result of suspended particles. This can generate higher filtration costs and an aesthetic degradation for recreational uses. In-stream attenuation of fine sediment, however, can also contribute to improved water quality. Nutrient spiralling can transform and promote the uptake of inorganic nitrogen and phosphorus (Davies-Colley, 2013). This clarifies water through the exchange of bed sediment with water and its constituents thus reducing particulate contaminants and increasing ‘filtration’ by plant and respiring biomass.

1.2.4.2 Nutrient mobilisation

The mobilisation of nitrogen and phosphorus from livestock pasture to waterways can occur as a result of overland flow (carrying particulate nitrogen and phosphorus) and by direct deposition of livestock urine and dung into waterways (Davies-Colley, 2013). Large fluxes of labile nutrients of phosphorus and nitrogen in dissolved, organic or particulate forms can also be transported in surface runoff water (Hooda et al., 2000). Nutrient application rates of 130 kg N/ha and 35 kg P/ha are typical in sheep dung patches (Williams & Haynes, 1995). Water quality is directly influenced by nitrogen, phosphorus and sediment both indirectly and directly through desorption-sorption reactions (Bargh, 1977;

Hallama et al., 2019; Monaghan, Hedley, et al., 2007). As water moves through the soil, freely mobile nitrate ions in the soil solution are at risk of leaching below the root zone. Cation exchange mechanisms retain ammonium ions in the soil but may be mobilised during surface runoff events (Hooda et al., 2000; Withers et al., 2014). Nutrient loss to waterways is primilarly driven by the volume of surface and subsurface runoff which occurs in a landscape. Soil types and slopes can also influence the amount of runoff and leaching which occurs. The amount and type of nitrogen and phosphorus mobilised from agricultural landscapes is influeced by the form and concentration of these nutrients.

2.4.2.1 Nitrogen

The largest source of N in New Zealand's waterways is from the urine of farm animals (Wright, 2012). Sheep urine contains a range of nitrogen forms and concentrations. The concentration of N will depend upon the *in vitro* microbial nitrogen conversion efficency, individual animal biological processes and the nitrogen present in the sheep's food source. Nitrogen concentration ranges from 3.0 to 13.7 g N/L^{-1} of fresh urine of which a majority is present as urea followed by creatine, hippuric acid and allantoin (Bristow et al., 1992; Hoogendoorn et al., 2010). At high stocking rates, and when soil nitrogen availability exceeds plant demand, the excess soluble nitrogen (mostly nitrate) leaches into the ground water or can be lost in surface runoff. The amount of N in surface runoff is strongly influenced by a combination of land use and management practices, soil types and climatic conditions (Chibuike et al., 2021; Hooda et al., 2000). Upon infiltration, soil water is partioned into lateral flow or deep percolation which ends up in surface or groundwater enviornments (Espanto, 2015). Ammonia concentrations in surface waters are generally very small due to the average pH of most surface waters being sufficiently low to convert all ammonia to ammonium ions (Hooda et al., 2000). This limits the denitrification process and reduces the amount of gaseous N released.

2.4.2.2 Phosphorus

Within a catchment, permanent features that contribute disproportionately greater P loads are defined as critical source areas. In comparison, variable source areas near streams are associated with mineral and organic particles that is lost via overland water flow (Dougherty et al., 2004; Syers et al., 2008; White et al., 2009). Phosphorus as fertilizer is usually applied in excess of most plant requirements. Due to many soils strong adsorption, microbial community and rapid precipitation, P in both the mineral and organic form is immobilised and thus accumulates in the soil (Hallama et al., 2019;

Menezes-Blackburn et al., 2018). The inorganic soil P pool is generally very small as this is readily available for uptake by plants. Eroded soil particles enriched with P from excessive amounts of P fertilizer or animal manure is susceptible to be transported from soil to water (Syers et al., 2008). Phosphorus can also be lost in its dissolved form; however, this is more common on high Olsen P soils which have good ground cover and minimal sediment loss. Any activities which increase the amount of P in soils, such as increased stocking rate, fertiliser application or brought in feed, will increase the risk of P loss to waterways. The phosphorus anion absorbs strongly to the positively charged soil particles, so P leaching is generally a minor pathway of P loss in NZ soils. Phosphorus transport in surface runoff occurs both in soluble and in particulate forms (Dougherty et al., 2004; Hooda et al., 2000). In hill country soils, where soil erosion tends to be elevated, particulate loss of P is the dominant form of P loss. Phosphorus drainage by preferential-flow, low P retention due either to P-saturation or inherently low sorption capacity may increase P leaching potential (Hooda et al., 2000). Particulate phosphorus forms constitute a major proportion (45% - 86%) of total phosphorus lost from catchments (Hooda et al., 2000). Higher rates of soluble P exported to water may be adsorbed to the river bank or river bed sediments and/or diluted during high flow periods reducing any direct ecological impact of this fraction for much of the year (Withers et al., 2014).

1.2.4.3 Microflora

A myriad of bacterial and protozoan pathogens exists within the faeces of grazing animals and consequently the soil (Alegbeleye & Sant'Ana, 2020; Martinez et al., 2009; Samaddar et al., 2021). Contamination of water with excrement can occur through a variety of pathways and therefore represents a potential health risk to human and animals (Zahedi et al., 2020). The risk potential will depend on a number of factors, such as animal health, severity of infection, stocking density of grazing animals and survival time of the organisms (Hooda et al., 2000). Factors likely to contribute to a pathogen load in water on farm includes undulating topography, bare soil surrounding dams, and high intensity rainfall events (Guo et al., 2022; Martinez et al., 2009; Zahedi et al., 2020). Traditional assessment of bacterial contamination in runoff water uses bacterial indicators, such as faecal coliforms (FC), total coliforms (TC), enterococci or faecal streptococci (FS) (Hooda et al., 2000; Oliver et al., 2012). Faecal Microorganisms (FMOs) are indicated by the proxy *Escherichia coli* (McDowell & Wilcock, 2008; Monaghan et al., 2021; Oliver et al., 2012). There are four categories of microbiological contaminants in order of decreasing mobility in water due to an increase in size: viruses, bacteria, protozoan cysts, and worm parasites (Davies-Colley, 2013; Guo et al., 2022). They are readily transmitted between animals and humans and are a threat to human users of water.

2.4.3.1 E. Coli

When using *E. coli* as a proxy for pathogens present in pastoral streams, the history of stock in the contributing catchment will be reflected. *E. coli* in the range of 200-500 *E. coli*/100 ml^{-1} has a high correlation with incidence of disease in fresh waters of New Zealand used for contact recreation (Donnison et al., 2004). Sheep have higher *E. coli* loading rates per hectare of pasture compared to cattle (Collins et al., 2007; Moriarty et al., 2011; Oliver et al., 2012). This may be linked to sheep faeces having a 'pellet-like' form compared to dung pats that may integrate more easily with the root mat. Therefore, models that predict bacterial concentrations in streams draining from small headwater catchments need to account for bacterial dynamics that are strongly influenced by inputs from the land (Collins et al., 2005).

Bacteria survival and concentration within animal faeces is influenced by the bacterial strain, the animal's diet, nutrients, solar radiation, moisture content, temperature, and pH (Bradford et al., 2013; Moriarty et al., 2011; Rusiñol et al., 2016). Water moving over land can entrain *E. Coli* and transport it in suspension to waterways (Bradford et al., 2013; Dymond et al., 2016; O'Callaghan et al., 2019). The state in which the bacteria occurs is an important factor when determining bacterial transport as bacteria attached to soil particles, occurring as single cells or present in flocs of cells have different transport mechanisms (Muirhead et al., 2006). On steep pastoral land, substantial levels of faecal bacteria can be transported directly to the stream network by overland flow(McDowell & Wilcock, 2008). Collins et al (2005) reported peak *E. Coli* concentrations ranged between $5x10^3$ and 7 $x10^6$ MPN/100ml and during heavy rainfall events, $2x10^5$ to $6x10^8$ *E. coli* per m^2 of hillside were delivered to a headwater stream. *E. coli* is generally filtered by water moving through the soil, except when drainage occurs through large cracks and pores. Muirhead et al. (2006) estimates that before bacteria could be filtered by grasses, they would need to be attached to soil particles greater than 63µm in diameter to settle out of overland flow and would need to be in large flocs 500µm in diameter. This issue could be potentially dangerous following a rainfall that exceeds the soils infiltration rate such as an event following a drought. The cracking of the ground due to a moisture deficit could see large quantities of *E. Coli* entering the groundwater and subsurface reservoirs.

2.4.3.2 Giardia

The *Giardia labbila* organism is excreted as small cysts in large numbers during an infection in animals. Young animals generally have a more prevalent infection compared to adults and infected-waste in runoff may contaminate fresh waters (Hooda et al., 2000). Oocysts in faeces shed in high concentrations from infected sheep can survive in cool and moist environments for long periods, leading to surface water and environmental contamination (Zahedi et al., 2020).

2.4.3.3 Cryptosporidium

One of the greatest concerns to health, *Cryptosporidium parvum*, is a protozoan parasite found in surface waters, thought to originate from livestock waste and is the causative agent of cryptosporidiosis (Hooda et al., 2000). Cryptosporidium oocysts may remain viable in water for over 140 days (Ramirez et al., 2004). Cryptosporidium oocysts show downward migration through the soil under intensive livestock systems, or where concentrations of livestock waste is prevalent, potentially transferring to water with subsurface runoff (Hooda et al., 2000). A single oocyst in susceptible hosts is sufficient to produce infection and disease. Oocysts are commonly transmitted through direct host-to-host contact by the faecal-oral route, and indirect contamination of water or food (Ramirez et al., 2004).

2.4.3.4 Campylobacter

The Campylobacter pathogen is likely to cause human waterborne related illness. Increased probability of campylobacter infection has been identified by the indicator, *E. coli*, in the range of 200-500 *E. coli*/100 ml^{-1} (Donnison et al., 2004). Campylobacter is intermittently shed by sheep depending on season. Campylobacter shedding rates coincide with increased stress, movement onto new pasture, and are highest during lambing and weaning and lowest during winter (Stanley & Jones, 2003). Increased shedding rates have also been linked to abrupt changes in diet. Faeces containing campylobacter are the primary source of transmission either via overland flow or percolating down into groundwater reservoirs.

1.2.5 Water Processes

When considering the impact that sheep have on water quality in a hill country setting, it is essential to understand the factors that generate stream flow, and how these exacerbate the influence that sheep may have on water quality. The competing factors in streamflow generation are influenced by a multitude of internal structure characteristics such as topography, land use, vegetation and lithology, soil type and external forces such as climate (Xiao et al., 2019).

1.2.5.1 Lithology and Topography

Soil properties and topography occur from tectonic forcings, lithological starting material and the climate (McDowell & Wilcock, 2008; Xiao et al., 2019). The South Island's west coast is home to New Zealand's oldest rocks (granite, greywacke, schist). The basement rock of the mountain ranges in both the South and North Island's is predominately greywacke (hard, composite sandstone), but in the south-west there are also areas of granite, gneiss and schist (McMillan et al., 2016). Highly porous pumice/tephra deposits over ignimbrite sheets stretch from the central volcanic plateau to the north-east coast creating the Taupo volcanic zone. This results in high infiltration rates to underlying aquifers that leads to high base flow and strongly damped flow responses (McMillan et al., 2016). On hill country sheep and beef farmland in New Zealand, the steep topography promotes the generation of significant surface water runoff under heavy and/or prolonged rainfall (Collins et al., 2007). Before reaching the channel network, up to 95% of the streamflow in hill country areas has passed over or through a hillside and its soil (Bronstert & Plate, 1997; Wittenberg, 1999). The topography of hill country sheep and beef farms exacerbates the convergence of subsurface and surface flows which causes saturated areas near stream channels and promotes the formation of wetlands. In the east areas of both islands, deposits of alluvial gravels and pumice create major aquifer systems. The buffering capacity of a floodplain is greatly reduced by permeable alluvium favouring subsurface flow and impermeable alluvium deflecting influent groundwater through aquifers across the floodplain surface or below the floodplain. (Burt et al., 1999). Nutrients that are lost to groundwater in upper catchments are then gained from groundwater in lower catchments, a result of confined layers of aquifer systems (McMillan et al., 2016). Less permeable soils such as clay may result in smaller leaching losses but increased losses in gaseous emissions due to increased denitrification and increased surface runoff (Hooda et al., 2000). Increased runoff, bank disturbance from livestock access to channels and hillslope erosion can mobilise fine sediment in streams that drain livestock pasture thereby reducing visual clarity and water quality (Davies-Colley, 2013).

1.2.5.2 Weather Inputs

1.2.5.2.1 Seasonal Effects

The weather in New Zealand is dominated by west to east moving mid-latitude depressions (McMillan et al., 2016) and baroclinic mid-latitude cyclones (Caloiero, 2015). Particularly in the South Island, mountain ranges lift oceanic air masses which cause high annual rainfalls that can exceed 10 m per year in the high axial ranges and low rainfalls in the eastern areas (less than 0.8 m) (McMillan et al., 2016). Variations in seasonal and annual precipitation occur due to a change in intensity of precipitation or the frequency of precipitation events (Caloiero, 2015). The lower North Island and the east of the South Island receive sporadic southerly fronts, resulting in cold temperatures, rain and snow. Heavy rainfalls in the east of North Island and far north occasionally occur from ex-tropical cyclones (McMillan et al., 2016). Water resources modified by a higher rainfall intensity include groundwater recharge, fluvial regimes and water availability (Caloiero, 2015).

Streams represent the surface expression of groundwater (Zimmer & McGlynn, 2018). A dynamic expansion and contraction of the stream network within headwaters occurs in response to seasonal rise and fall of the water table (Goulsbra et al., 2014; Zimmer & McGlynn, 2017; Zimmer & McGlynn, 2018). A reduction in stream velocity increases sedimentation and erosion in areas of high flow during summer (Champion & Tanner, 2000). Similarly, storm events associated with high peak flows during winter can result in stream bank erosion and higher levels of sediment deposition as stream plant biomass is low and flow rates are high (Ashworth & Ferguson, 1986; Champion & Tanner, 2000).

During periods of heavy precipitation associated with winter, the water table shifts the interface between stream channel and the catchment zone upstream (Goulsbra et al., 2014; Zimmer & McGlynn, 2017). This activates stream flow in previously dry channels which may in turn cause heavy nutrient loading of water bodies during periods of increased precipitation. In arid and semi-arid environments, intermittent and ephermal streams are often above the water table which may lead to substantial nutrient transmission losses through the unsaturated zone of the soil matrix (Goulsbra et al., 2014; Zimmer & McGlynn, 2017). Sheep tracking along hillsides can create channels for nutrients to mobilise and connect with a body of water. This is of particular importance as many hills grazed by sheep are dry at some times throughout the year. These previously dry areas can become conduits for soluble nutrients to enter the waterways adjacent and the expansion of channelised flow can contribute significant quantities of runoff and non-point discharge (Goulsbra et al., 2014; Zimmer & McGlynn, 2017). Throughout the year the deposition and transition of nutrients and sediment as a result of fluvial processes influences the wider environment. The spatial estimation of daily rainfall is critical when discussing stream flow and quality (Tait et al., 2012). Spatial rainfall is used in conjunction with hydrology models which is used to assess resource consent applications where maintenance of minimum flows, flood protection and degradation of waterways are of concern (Singh et al., 2019; Tait et al., 2012).

1.2.5.3 Fluid Dynamics

An intrinsic link exists between composition of sediment and the hydraulic properties of a streambed (Partington et al., 2017). Sedimentary composition involves complex erosion and transient processes. During periods of high flow, sediment is mobilised and, during low flow periods it is deposited. The catchment area of freshwater bodies influences the complex patterns of water fluxes and runoff generation resulting in sediment becoming more attenuated with increasing catchment size (McGlynn et al., 2004). The interaction between groundwater and surface water is complex and depends on the hydraulic connectivity between the groundwater and a stream as well as local geology (Yang et al., 2017; Zimmer & McGlynn, 2018). Streamflow generation revolves around discharge and storage relationships, the dynamics of connectivity, and catchment scale threshold behaviours (Xiao et al., 2019; Zimmer & McGlynn, 2018). The interaction of these processes, combined with a myriad of connected hydrological pathways, contribute to the generation of flow within freshwater bodies. Stream baseflow is slowly generated through the soil matrix while surface runoff enters into the stream rapidly (McDowell & Wilcock, 2008; Singh et al., 2019). Groundwater levels are linked to groundwater abstraction and stream flows, vegetation water use, and fluctuations in seasonal and annual weather (Caloiero, 2015).

1.2.5.4 Transport Pathways

A nutrient budget of input versus output within a farm system considers intentionally managed imports such as fertiliser and unintended nutrient transfers from hydrological and atmospheric processes (Fonte et al., 2012; van der Heijden et al., 2013). The movement and transition of nutrients and sediment as a result of erosion and hydrological processes can impact water quality. The source of contaminant generated on the farm influences its transition through to waterways. The relative loss of N and P to surface waters can occur from changes in land-use. A mosaic of rolling, hilly and mountainous landscapes all create differing degrees of hydrological processes and effects (Bronstert & Plate, 1997; Hauer et al., 2016). Furthermore, the impacts that nutrients transported to surface waters have may vary depending on their entry routes. Agricultural nutrient loads are diffuse in nature and storm-dependent resulting in difficulty mitigating their effects on water quality (Bryan & Kandulu, 2011; Withers et al., 2014). The hydrological pathways govern the flux of nutrients, sediment and substrates across and into a farm system and are also responsible for their concurrent transport essential for effective transformation and removal (Burt et al., 1999; McDowell & Wilcock, 2008). The transfer of contaminants across the farm system into the waterways depends on the source and mobility of the contaminant.

2.5.1.1 Direct Deposition

Direct pathways of contaminants into waterways involves faecal matter being directly deposited or close enough that wash-in potential is high (Collins et al., 2005; Collins et al., 2007). This distinction is critical as there is no opportunity for microbes in the faecal matter to die-off before direct deposition into water. Camp sites tend to receive defaecation deposits 2-3 times greater than necessary for annual pasture uptake (Rowarth et al., 1985). Rainfall and irrigation largely influence indirect pathways to transport microbes. This creates an opportunity for the attenuation of faecal contamination via microbial die-off or immobilisation (Collins et al., 2007; McDowell & Wilcock, 2008).

2.5.1.2 Riparian damage

A riparian zone could be described as the banks of a river, or a strip of land on either side of a water channel with the function of a natural sink to intercept, transform and/or remove nutrients, contaminates, pollutants and sediment generated from farmland (Burt et al., 1999; Fernandez, 2017; McKergow et al., 2016). Riparian systems prominent feature is their connectivity with larger watersheds and other riparian zones creating an interface with adjoining terrestrial environments (Belčáková et al., 2019; Daigneault et al., 2017). In New Zealand, minimal riparian buffers with widths of 2 to 5 m are commonly used to exclude livestock (McKergow et al., 2016). Riparian zones sustain water quality derived from land use activities by limiting stream bank erosion which greatly reduces sedimentation from bank erosion and maintains in-stream biodiversity by sequestering nutrients and toxins thereby reducing contamination from N, P and pathogenic bacteria (Daigneault et al., 2017; Fernandez, 2017; Hefting et al., 2003). Smith (1989) showed that retired waterway buffers between 10 and 13 m in width, vegetated with white clover and perennial ryegrass, resulted in suspended sediment concentrations in runoff reducing by up to 90% when compared to unretired grazed sites. When comparing to those occurring from similar slopes without a buffer region, riparian zones can reduce phosphorus losses and sediment losses up to 59% (Gillingham & Thorrold, 2000).

When a riparian zone becomes saturated during a flood or during periods of prolonged precipitation (winter), a pool of carbon created by submerged plant root systems and their associated fungal communities is utilized by the development of anaerobic bacterial communities (Burt et al., 1999). These anaerobic communities could potentially denitrify nitrate-N to nitrogen gas, reducing the risk of nitrate-N loss to waterways (Rivett et al., 2008). As oxic groundwater moves through wetlands, it rapidly becomes suboxic or anoxic vigorously consuming available oxygen due to its decomposition processes therefore, removing nitrate (NO_3) from groundwater through denitrification (Burns & Nguyen, 2002; Rivett et al., 2008). A shallow water table present in wetlands allows contact between groundwater and the root zone, creating important processes for NO_3 removal through microbial immobilisation and plant uptake (Hefting et al., 2003). Factors such as the C:N ratio, plant uptake rate of NO_3 and NH_4, organic carbon (C) content, decomposition rate of soil organic matter, flow rate of water through the wetland, and groundwater concentration of NO_3 and NH_4 that discharges into the wetland influence the rate at which wetlands can transform and cycle nitrogen (N) (Burns & Nguyen, 2002; Rivett et al., 2008). The concentration of nutrients entering the riparian zone is influenced by land management factors such as stocking intensity, fertiliser inputs and hydrological processes that transport the nutrients to the riparian zone. Repeated floods leave fertile fine-grained river sediments behind on riparian soil. Riparian land could be valuable for the production of food and fodder biomass (Blankenberg & Skarbøvik, 2020). The increased biomass growth may encourage the preferential grazing of livestock within a riparian zone, further increasing the risk of excretal deposition and trampling damage. Damage to this zone may release previously stored nutrients directly into the waterway, in the form of sediments or plant matter. Slow recovery rates in structurally poor soils have an elevated risk of soil erosion and losing contaminants in runoff as a greater volume of surface runoff is produced by a decrease in soil infiltration rate (Cournane et al., 2011). Pugging damage compacts the soil aggregates and increases the anaerobic properties of the soil that can cause elevated levels of nitrification occurring. Pugging and trampling by stock actively mobilise sediment within the riparian region and increases in stream attenuation of sediment.

2.5.1.3 Stream bank erosion

Bank erosion is naturally occurring in most rivers. It can be enhanced by the removal of vegetation which causes a loss of land and danger to infrastructures. Water pollution increases as a result of mass failure and erosion of stream banks; the largest contributor of soil particles and sediment to a waterway (Blankenberg & Skarbøvik, 2020; Fox & Wilson, 2010). Through compaction and trampling by stock, natural erosion and severe weather events, nutrients can be released into freshwater bodies (McDowell & Wilcock, 2008). The severity of streambank erosion can be classified by the physical parameters of the streambank. These include the proportion of reach affected, the length of streambank actively eroding, the height of streambank actively eroding and the physical nature of streambank materials (Fox & Wilson, 2010). An assessment of whether the streambed is aggrading or degrading, the lateral distance eroded into terrace and the likelihood of stabilisation if soil conservation measures are implemented, will generate information on stream bank conditions (Lynn et al., 2009). Removing livestock from riparian areas and planting trees and small shrubs in lower reaches of a catchment is unlikely to have a significant effect on reducing the contribution of sediment from these reaches (Hughes, 2016). Different erosion processes acting on stream banks (e.g., fluvial entrainment, mass failure, and preparatory processes) and inter-annual variability in sediment yields likely contribute to this result (Fox & Wilson, 2010; Hughes, 2016). Excluding livestock from riparian areas may reduce sediment generated from livestock trampling stream banks but the loss of protective groundcover caused by riparian shading may result in more sediment entering waterways.

2.5.1.4 Surface Runoff-Overland flow

Surface runoff provides a rapid delivery of nutrients into the water body. When rainfall intensity exceeds the infiltration capacity of a soil, surface runoff occurs (Buda et al., 2009). Infiltration refers to surface water that enters into the soil water table alongside unsaturated downward flow and different soils vary across the landscape (Dougherty et al., 2004; Freeze, 1974). Saturation of the soil profile results in surface soils having significant potential for lateral flow (overland flow) to occur (Buda et al., 2009; Weiler & McDonnell, 2006). Compaction and pugging of the soil surface, particularly in high traffic areas (troughs, gateways, stock camps), reduces soil infiltration rates via a decrease in macro porosity thereby promoting increased likelihood of surface runoff occurring (Cournane et al., 2011; Dougherty et al., 2004). If the soil is unable to absorb the nutrients available, high rainfall and overstocking may result in significant surface runoff.

2.4.1.5 Subsurface Flow

Subsurface flow occurs when there is a sufficient degree of connectivity and infiltration into the soil matrix resulting in quick transmission of soil water laterally downslope into waterways (Bronstert & Plate, 1997; Weiler et al., 2006). Water enters the soil through infiltration and leaves through evaporation or by percolating through to the saturated zone (ground water) (Harding, 2004). This water movement transfers nutrients through the soil inevitably into freshwater bodies. This process is generated by the hydraulic head that induces seepage flow through the preferential flow pathway causing focused discharge that can impact significantly the migration of soil water through the lateral channel (Fox et al., 2011; Weiler et al., 2006). Ground water discharges and sub-surface flow draining grassland contribute significant concentrations of labile substrates to streams and other watercourses (Hooda et al., 2000; Weiler et al., 2006). This process accounts for some of the nutrient in water, particularly nitrate-N. Subsurface flow and drainage highlight the role of soil characteristics, climate, land management and topography as contributing factors to nutrient transfer risk (Collins et al., 2007; Weiler et al., 2006).

2.4.1.6 Leaching

Leaching is the process where nutrients percolate through the soil profile into subsurface or groundwater (Jahangir et al., 2012; Withers et al., 2014). Dissolved P and nitrate, due to their solubility in water, are susceptible to leaching. Leaching occurs when the application of fertiliser, manure or urine exceeds the soil and plants capacity to utilise these nutrients and the net flow of water is into the soil (below field capacity) (Dinnes et al., 2002). The water adsorbs the soluble nutrients and travels through the soil matrix into the groundwater reservoir. The amount of rainfall and the concentration of leached nitrate show an inverse relationship (Hooda et al., 2000). P leaching is an insignificant fraction of P losses, due to the strong retention of P in New Zealand soils with the exception when P retention is low. However, high inputs of P into a system, increase the risk of P leaching through saturating P sorption capacities of soils (Hooda et al., 2000; Withers et al., 2014).

Nutrient losses have deleterious impacts on regional water quality and downstream aquatic ecosystems and decrease the fertility of agricultural soils (Withers et al., 2014). Reducing the availability of nutrients during times of low plant demand, increasing nutrient storage capacity and organic matter of soils are management strategies to control nutrient loss risk (Fonte et al., 2012). Different soil types, nutrient legacies and stocking rates intensity will influence the potential nutrient loss of an environment through the processes of water movement leaching risk (Refsgaard et al., 1999; Withers et al., 2014). Sheep can influence nutrient loss through their interactions with the environment, through treading damage, nutrient deposition, and grazing location. This will ultimately influence the effects sheep have on water quality.

1.3 Sheep Behaviour

Sheep are highly vigilant and show flock-based patterns of vigilance and alarm that can make sheep seem fearful and anxious (Dwyer, 2008; Wemelsfelder & Farish, 2004). Environmental factors can influence behavioural differences between breeds through learning that arises from differences in their rearing environment (Villalba et al., 2009). If sheep experience fear or discomfort in the presence of a stimuli or events they learn to avoid those stimuli (Boissy et al., 2007; Wemelsfelder & Farish, 2004). A sheep that experiences discomfort within their environment exhibit decreased grazing and drinking behaviours (Cockram, 2004).

Sheep exhibit learned behaviours such as the reduced ingestion of gastrointestinal parasites in their infective stages during grazing (Gougoulis et al., 2010; Hutchings et al., 1998). Sheep have also been observed to avoid grazing faeces contaminated swards or reduce their grazing depth which reduces the likelihood of ingesting parasites (Forbes & Hodgson, 1985; Gougoulis et al., 2010).

The behaviour of sheep is influenced by group size, as individuals show strong flocking and leadership behaviour (Dwyer, 2008; Wemelsfelder & Farish, 2004). Sheep in large groups display reduced synchrony of feeding and resting and increased variation in resting time compared to smaller groups (Jørgensen et al., 2009). The intensity of agonistic and maternal behaviours, flocking responses and gregariousness are significantly different among sheep breeds (Boissy et al., 2007; Dwyer, 2008; Villalba et al., 2009). All breeds exhibit strong own-breed preferences (Arnold & Pahl, 1974) and tend to form strong associations within their own breed.

1.3.1.1 Grazing behaviour

Sheep generally show two high intensity grazing periods at sunrise and sunset (Das et al., 1999; Dwyer, 2008; Gonyou, 1984; Squires, 1975). Their daily grazing pattern creates circadian variation in the rate of consumption and feed intake (Alvarenga et al., 2016; Rutter, 2006). In the period between midmorning and mid-afternoon sheep are the least active; where the primary activities are sitting, lying and ruminating (Squires, 1975). Spatial memory enables grazing animals to exploit desirable food locations in a heterogeneous environment (Dumont & Petit, 1998; Hewitson et al., 2005). Foraging is a process where a trade-off, independent of past experience, is undertaken by a sheep for the potential food gains of a particular energy source or to keep searching for an alternative food item (Dumont et al., 2007; Pyke, 1984). A sheep will undergo this cost benefit analysis upon contact with a food source. The quality and quantity of the food source is dependent on the physical properties of the environment, such as light interception, water availability and the nutrient status of the soil.

Sheep are typically classified as social animals and their social facilitation results in the synchronisation of the start of grazing bouts (Penning et al., 1993). Vigilance behaviour of ewes, dietary choices and foraging location is affected by a sheep's distance from their flock, the size of their group and the preferred feeding site (Dumont & Boissy, 2000). Preferences for plant species is based on previous experience. A sheep may sample unknown forages before grazing or search the pasture extensively if relocated to pasture that contains a range of unfamiliar species (Gonyou, 1984; Rutter, 2006).

Days are generally short in winter resulting in low pasture quality which generates a requirement for continuous grazing throughout the day (Gonyou, 1984). In contrast, during summer, sheep spend more time in the shade resulting in no distinct peaks of grazing bouts during the day (Dwyer, 2008). A study conducted in Ireland by Williams et al. (2010) conducted visual observations of Scottish Blackface ewes along an 8.2 km transect line, for five hours, twice weekly. They reported that the number of sheep observed to be grazing were greatest in winter whereas in summer and autumn the predominant behaviour was lying. Further analysis showed that the mean percentage of time spent grazing during the daytime sampling periods ranged between 63.1 and 94.6 % of sightings, followed by lying down (2.5 and 30.2 %). The primary source of variation was associated with season which may have been influenced by stocking rate which was 0.4 ewes/ha in spring, 0.9 ewes/ha in summer and autumn and 0.8 ewes/ha in winter. The challenge for accounting the variation in sheep behaviour throughout the day was highlighted by the short window of behaviour recording (Rutter, 2006) .

Betteridge et al. (2010) observed a diurnal synchronisation of grazing between 1000 and 1900 hours within a flock of 18-month-old Romney ewe hoggets in New Zealand stocked at 40 stock units/ha and eating activity to be greatest in the hour before sunset. Between 0200 and 0300 hours, brief grazing bouts were detected, and the lowest eating rate was observed between 0400 and 0700 hours. Photosynthetic material accumulates with the increasing dry matter content of the plant. This may enable sheep to eat a higher density of forage per mouthful which coincides with the increased eating activity (Betteridge et al., 2010). This phenomenon could be a behavioural strategy of sheep to maximise intake. The grazing behaviour of sheep is linked with the time of the day, stocking rate and season but accurate recording over a time period usually only accounts for a small proportion of the behaviour that occurs.

1.3.1.2 Drinking Behaviour

There is limited information on the drinking behaviour of sheep (Jongman et al., 2008). The availability of water can influence sheep movement. Sheep are averse to standing in water (Dymond et al., 2016) and farmed sheep prefer to graze within close proximity of a water source (Bailey et al., 1996; Dwyer, 2008; Fensham & Fairfax, 2008; Markwick, 2007). Sheep with access to water spent more time lying down (59%) compared with those without access (44%) (Jackson et al., 1999). This effect, however, was not correlated with environmental temperature. This may indicate that sheep spend more time actively searching for water if there is no readily available source. Al-Ramamneh et al. (2012) showed that sheep spent approximately 0.2% of a 24 h day drinking (2.66 minutes per day). They also observed that sheep visited water sources more often when time to access water was limited, thus during the hours of water availability sheep spent a more time drinking resulting in increased rates of water consumption was.

Drinking bouts in sheep are short, generally lasting less than a minute (Al-Ramamneh et al., 2010; Das et al., 1999). The amount of water that a sheep will drink depends on stocking density at the watering point, the degree of dehydration, time elapsed since the last drink, time allowed to drink, and the amount of forage previously consumed (Al-Ramamneh et al., 2012; Dwyer, 2008; Hall et al., 1997). The rate of water ingestion (volume of water consumed per minute) varies between individual drinking motivation and cannot be adequately evaluated by observation (Al-Ramamneh et al., 2012). Environmental conditions such as temperature and the provision of shade influence the water intake of sheep and variation between sheep breeds influences water consumption. Crossbred sheep need more water than merino sheep breeds (Dwyer, 2008; Markwick, 2007) and Johnson (1987) reported that water intake per kg ewe liveweight was 33% higher for Merino mixed age ewes that had access to shade when the ambient environmental temperature ranged between 20°C and 50°C. At temperatures between 0-15°C, sheep consume 2kg water/kg DM and above 20°C this ratio increases to 3:1(Marai et al., 2007). Behavioural adaptions to combat water shortages involve selecting shade or shelter dependant on weather (Dwyer, 2008). Water consumption by a sheep is greater in summer compared to winter (Macfarlane et al., 1958; Markwick, 2007). A trial of Scottish Blackface mixed age ewes found that temperature influenced the frequency of drinking bouts with 31 observations at 14°C and 41 at 21°C (Jackson et al., 1999). Water intake was defined as the muzzle of the sheep being immersed under water for more than 5 seconds.

Sheep have been observed to avoid standing in ponds and sedge swamps and seem to prefer dry and poor grasslands compared to wetlands (Putfarken et al., 2008). Furthermore, in general sheep do not actively search for water points and avoid the channel and riparian zone of a waterway, not only the flowing or standing water (Collins et al., 2007; Plaza et al., 2020). Research of cattle in semi-arid areas of the United States has shown that providing an alternative water source is an incentive to entice them away from water channels (Collins et al., 2007). Under intensive stocking conditions in New Zealand, however, alternative water sources located on hilltops did not reduce the use of streams by beef cattle (Collins et al., 2007). A study of sheep showed that the water intake per ewe was 2 to 3-fold greater when multiple drinking sources were available compared to a single trough (McCoard et al., 2020). It was hypothesised that this was the result of a shorter walking distances to access a water trough.

Influencing the frequency of sheep that access waterways to drink by offering alternative sources such as a water reticulation system, could potentially minimise the impact of sheep around natural waterways.

1.3.1.3 Water requirements

Sheep water consumption varies depending on the type and size of the animal, their level of activity, climatic conditions, the animal's physiological state and stage of production (maintenance, growth, gestation, lactation) (Akinmoladun et al., 2019; Barros de Freitas et al., 2021; Dwyer, 2008; McCoard et al., 2020). Water represents 65% and around 77% of the live weight in adult and new born lambs respectively (Beede, 2012; Infascelli et al., 2005). The water requirement of sheep relates to their water inputs (water drunk, moisture content of forage, metabolic water) and water outputs (urinary, faecal evaporative and respiratory water loss) (Al-Ramamneh et al., 2010; Chedid et al., 2014). Therefore, the water intake requirement of sheep is a function of their physiological composition, superimposed over their environmental factors.

There are three main water sources for sheep: free water obtained by drinking; water contained in forage; and metabolic water (Chedid et al., 2014; Cordova-Torres et al., 2017; Schlink et al., 2010). Metabolic water is produced as the result of oxidation-reduction reactions within the body associated with the processing of carbohydrates, lipids and amino acids (Chedid et al., 2014; Infascelli et al., 2005). It is necessary to maintain a dynamic equilibrium between the quota of water taken in and that eliminated through the faeces, urine, milk, aqueous vapours in expired air, perspiration, and cutaneous transpiration (Infascelli et al., 2005) as water deprivation can alter the endocrine and metabolic balance of the animal (McCoard et al., 2020). Water is required as a universal solvent in the intracellular and extracellular compartments, such as hormones, transport of heat, nutrients, ions, and metabolites and for the elimination of metabolic products (Barros de Freitas et al., 2021; Beede, 2012). Discrepancies within the metabolic state can cause serious complications in efficient sheep production systems.

Barros de Freitas et al. (2021) reported that 94.92 % of the total water intake of 16 Santa Ines breed sheep (8 males and 8 females) and 16 crossbred 7/8 Dorper x Santa Ines (8 males, 8 females) was by drinking (voluntary consumption) and 5.08 % from the feed consumed. These animals were housed in indoors and fed bran commercial concentrate, 2.5 cm long chopped hay, had water and mineral salt *ad libitum*. The dry matter of the hay was 93% and the concentrate was 88.9%. These relatively dry feeds resulted in a water intake 'seesaw' effect where the low water content of the feed results in the sheep drinking more to balance body water requirements.

Water turnover rates are linked to the use of water in metabolic processes such as energy and protein synthesis and is a function of climate and species (Aganga, 1992; Marai et al., 2007; Schlink et al., 2010). During winter, the consumption of water ranges between 9-11% of total body weight and increases in summer to 19-25% (Marai et al., 2007). Among sheep, half of the water in the body is turned over in about 5 days, which is influenced by climate and physiological conditions (Infascelli et al., 2005) (Table 2). Sheep at various stages of their life relative to gender and productive ability influence their water requirements.

Table 2 Water requirements (kg/kg of dry matter intake). Adapted from Infascelli et al., 2005.

Physiological characteristic of Sheep	**Less than 16°C**	**16-20°C**	**Greater than 20°C**
Lambs up to 4 weeks	4.0	5.0	6.0
Growing subjects or non-pregnant adults	2.0	2.5	3.0
Central phase of pregnancy:			
1 lamb	3.0	3.8	4.6
2-3 lambs	3.3	4.1	4.9
Final phase of pregnancy:			
1 lamb	4.1	5.2	6.3
2-3 lambs	4.4	5.5	6.6
Lactation:			
First month	4.0	5.0	6.0
Second and following months	3.0	3.7	4.5

Thompson et al. (1989) noticed in yearling Romney ram with an average weight of 42kg, total water intake ranged between 1427ml and 1787ml. In comparison, Lynch et al. (1972) observed Merino sheep with an average weight of 47kg, rarely exceeded a water intake of 800 ml/day. In addition, from May to September, water intakes ranged between 0.1 and 1.0 l/day, probably associated with colder weather and as the weather warmed, water intakes increased gradually to between 1.5 and 3.5 l/day during lactation. Al-Ramamneh et al. (2010) reported water intakes in adult German Black head ewes kept in temperate conditions ranged between 2 and 4.6 l/kg of dry matter intake (DMI) which then increased to 4.2 and 12 l/kg DMI under arid conditions. Ewes were fed ryegrass hay with an average dry matter content of 85.7%. Furthermore, Barros de Freitas et al. (2021) reported that for sheep kept at 16 to 25°C, water intake was between 4 and 6 l/kg DMI whereas at 15°C intake was 2 l/kg DMI.

1.3.2 Factors influencing sheep drinking behaviour

1.3.2.1 Wool length

Extreme conditions such as high temperatures can increase the water consumption of sheep by 78% (Markwick, 2007). Wool length markedly impacts heat transfer and metabolic processes

(Akinmoladun et al., 2019; Beatty et al., 2008; Dwyer, 2008). The presence of fleece is associated with an increased body temperature. Heat dispersal through vaporisation from the skin and respiratory passages, conduction and radiation at environmental temperatures lower than body temperature are remarkably constant and is influenced by the length of wool (Joyce & Blaxter, 1964). Compared with shorn sheep, fleeced sheep have higher water intakes and respiratory rates (Beatty et al., 2008). A sheep will require more water when it has a longer fleece to regulate their body temperature resulting from an increase in endogenous heat production (Al-Ramamneh et al., 2012; Joyce & Blaxter, 1964). The insulation effect formerly provided by the fleece is lost after shearing which increases the heat load on sheep in summer (Alqaisi et al., 2020). The sheep adjusts to a rise in ambient temperature by increasing their evaporative cooling adaptions; through panting (to increase evaporation within the respiratory track), sweating and can be accompanied by a reduction in feed intake and water lost via urine and faeces (Dwyer, 2008; Marai et al., 2007). The legs and ears of sheep contribute about 23% of the body surface area and at ambient temperatures of 36°C, these area dissipate a high proportion of the heat (Marai et al., 2007). This may create enhanced energy exchange between the sheep and its surroundings. These effects are important as they can influence the amount of water a sheep will require to drink. Aguilar et al. (2020) reported that unshorn Merino Wethers spent up to 13 min longer per day at the water trough than shorn ewes for at least 9 days after shearing. This suggests fleece retention on unshorn sheep results in a higher water requirement.

1.3.2.2 Feed availability

Sheep alter their grazing behaviour to achieve long term rates of energy intake and daily intake requirements (Chapman et al., 2007; Villalba et al., 2015). During the dry season, feed availability is often at low densities per unit area and of low quality and sheep adapt to these conditions by dispersing more widely and increasing the grazing time during the day (Gougoulis et al., 2010; Manteca & Smith, 1994). The length of time spent grazing may be influenced by solar radiation or fly irritation (Gougoulis et al., 2010; Manteca & Smith, 1994; Maurya et al., 2012). Sheep graze selectively from a mixture of plant species differing in edibility, nutrient status, quality, and density (Manteca & Smith, 1994; Parsons et al., 1994; Villalba et al., 2009). A sheep's foraging decision is based on personal preference resulting from previous experience and abiotic and biotic factors. By consuming a variety of plant species, a sheep obtains a more beneficial mixture of nutrients which influences the animal's decision to walk for a preferred forage, when a poor-quality alternative may be available (Dumont & Boissy, 2000; Villalba et al., 2009). Sheep may graze approximately 80% of the grass height (exposing bare soil), leaving it susceptible to erosion which increases the risk of nutrient and pathogen transfer (Julian, Beurs, et al., 2017).

Hill country pastures of New Zealand typically have small areas of flat to gently sloping land. These are often at the top or bottom of a hill, although some low-slope areas can be found within steeper slopes and around stock tracks (Betteridge et al., 2017). Low fertility hill soils generate 6 to 9 t DM/ha/year in pasture production which can support 10 to 12 sheep stock units (su)/ha (Lambert et al., 2000). Compared to hill soil pastures supplemented with nitrogen, these high fertility pastures can support 26 su/ha (Lambert et al., 2003). Additional fertiliser inputs increase the likelihood of nutrient loss from the farm system.

A sheep's water requirements are regulated by factors such as environmental temperature, dry matter intake, and metabolic water use (Alqaisi et al., 2020; Marai et al., 2007). Sheep satisfy their water requirements by food intake and dew in the absence of drinking water (Lynch et al., 1972; Putfarken et al., 2008). Sheep select a diet that is more digestible favouring green forage but when green forage is sparse, lower digestibility dead material is included (Gonyou, 1984). Fresh forages (80-85% of water) is enough to meet the requirements but can be limited by metabolic processes such as urinary, faecal and endermic elimination (Infascelli et al., 2005). Most breeds of Sheep in New Zealand have negligible water reserves and water fasting may cause serious health and production consequences. Sheep catabolise their own adipose and protein reserves in conditions when 10% of body water per kilogram of weight is lost (Casamassima et al., 2018; Dwyer, 2008; Infascelli et al., 2005).

1.3.2.3 Feed composition

In New Zealand pasture provides over 95% of the diet of sheep (Morris, 2009). Hill country pasture composition has been developed during the last 120 years and typically comprises 15 to 25 species m^2, a combination of legumes, grasses, and other dicotyledonous cultivars (Dodd et al., 2004). Pasture communities in hill country farms have adapted to temporal and spatial variation in environmental and edaphic conditions, including low fertility and soil pH, variable rainfall, contrasting soil moisture contents on different slopes and frequent grazing events (Dodd et al., 2004; Dodd et al., 2020).

New Zealand's pastoral systems are dominated by perennial ryegrass, *Lolium perenne* and white clover, *Trifolium repens* but low fertility grass species are also an important component (Dodd et al., 2004). Herbage digestion releases an array of metabolites and nutrients into the rumen which are absorbed across the rumen wall, passed to the small intestine and absorbed there and are then passed via excretion (Chapman et al., 2007; Dwyer, 2008). Reduced voluntary water intake is a result of a reduction in the dry matter content of pasture (Forbes, 1968). Water-soluble carbohydrates contained in fresh forages are the dominant source of energy available to sheep (Lee et al., 2001). A herbage diet rich in protein results in an increase in the water requirement of the animal as protein synthesis relies upon the provision of energy and protein nitrogen to the rumen microbial population which is limited by metabolic water availability. High concentrations of rumen degradable protein found in plant species such as white clover result in rapid degradation in the rumen leading to high concentrations of ammonia in the rumen fluid (Chapman et al., 2007; Cheng et al., 2013). Elevated ammonia levels may pose a toxicity threat to the sheep. High concentrations of ammonia in the rumen fluid also pose an increased risk of nitrogen concentrations leaving the sheep in urine and excreta. To avoid eating during the night, sheep consume forage with a slow rate of digestion and high in fibre at dusk (Raeside et al., 2016). This may influence their spatial distribution during this feeding period towards forages high in moisture and those near waterways for example. Lush, moist grasses/species that grow close to a stream that have a readily available source of water can grow faster and denser swards.

The satiety theory predicts that sheep will select a diverse diet when one food source alone could satisfy their nutritional requirements (Chapman et al., 2007; Villalba et al., 2015). Sheep choose a mixed diet when offered between forage species presented in a pasture community (Hill et al., 2009). Oro-sensorial properties such as smell, taste, and irritation of foods and their post-ingestive consequences determine the acceptability and grazing choices of sheep (Squires, 1975; Villalba et al., 2015). Various parts of the same species at different stages of growth will also influence sheep selection. Parts high in nitrogen are generally eaten first, the leaf is always eaten in preference to the stem. Distribution of mixed swards across a hill block are linked to sheep accessibility, nutrient availability, and growing conditions relative to light interception and plant available nutrients.

1.3.2.4 Excretion Behaviour

Faecal matter creates hotspots of biological activity and may be considered a low-density organic sediment or bio-colloid (Davies-Colley, 2013; Leiber-Sauheitl et al., 2015). Sheep faeces contain active microbes, labile substances, and a C:N ratio narrower than most soil organic matter components (Leiber-Sauheitl et al., 2015). Deposition of excreta by sheep are influenced by animal grazing and resting behaviour and spatial pasture production (Saggar et al., 2015; Schlecht et al., 2006). Although beneficial in returning nutrients to the soil in a plant-available form, faecal deposition on hill slopes supplies only a small proportion of the nutrient requirement of pasture. The proportion of faecal deposits decreases sharply with increasing steepness of the slope (Rowarth et al., 1985).

Sheep appear to camp during the night in less steep areas, generally at the top or bottom of the paddock (Dwyer, 2008; Thorrold et al., 1985). The aggregation of sheep in stock camps results in a concentrated deposition of nutrients via faeces and urine to a small area of a paddock in excess of plant requirements which increases the risk of nutrient loss through leaching and volatilisation (Betteridge et al., 2010; Grassia, 1978; Thorrold et al., 1985). Faeces initially accumulate in areas which are not grazed during the day, with defaecation occurring at a higher frequency in camp sites resulting in the nutrient load from faecal sources being 2 to 3 times greater than annual pasture uptake (Rowarth et al., 1985; Thorrold et al., 1985). The deposition of faeces near or in waterways poses a significant risk to stream health and biodiversity (Collins et al., 2007). Fencing can potentially reduce the input of faecal material directly to waterways but can pose a risk of physical injury to the sheep (Jouven et al., 2012; McKergow et al., 2016). The provision of water, shelter and shade away from the stream can encourage livestock to dissipate from this area (Collins et al., 2007).

1.3.3 Location Characteristics

1.3.3.1 Paddock contour/aspect

Approximately 40% of New Zealand's surface area can be defined as steep hill country and to avoid cultivating highly erodible soils and minimise soil disturbance on farmed hill country, livestock grazing systems rely on perennial pastures (Tozer et al., 2021; Tran et al., 2020). Micro-environmental characteristics related to elevation, slope and aspect generate a high diversity of vegetation in hill country farms (Betteridge et al., 2017; Dodd & Sheath, 2003). Foraging by intra- and interspecific competitors, fluctuating weather and rainfall conditions and spatial variation in vegetation cause pasture quality to differ across different slopes and aspects (Dodd & Sheath, 2003; Hewitson et al., 2005). Pasture growth production and plant species distribution influence where animals prefer to graze (Betteridge et al., 2017). The transfer of plant nutrients by livestock from cool to warmer areas and slopes to flatter areas may result in elevated soil pathogen, nitrogen, phosphorus and potassium concentrations.

Pastoral hill country farms systems usually utilise year-round animal grazing *in situ* to improve efficiency in labour requirements and forage harvesting ability. The chemical and physical disturbances associated with grazing livestock and a range of aspect, wind and slope combinations influence sunlight interception, moisture and temperature regimes (Dodd & Sheath, 2003). Therefore, pasture production and composition vary across the topography. Typical hill country pastures are based on brown-top (*Agrostis capillaris*), ryegrass (*Lolium perenne*) and clover mixes (*Trifolium repens)* , with high fertility areas dominated by ryegrass and clover and low fertility areas dominated by brown top (Suckling & Forde, 1978; Tozer et al., 2021; Wedderburn et al., 1996). Legumes are generally sparse on north-facing slopes as they may show signs of nitrogen deficiency more than south faces (Betteridge et al., 2017). The combination of the grazing tolerance of grass and high photosynthetic assimilation capacity with the nitrogen fixing capacity of legumes maximise pasture production (Tozer et al., 2021; Williams & Haynes, 1990). South-facing slopes are wet and cold in winter generating slow pasture growth rates but are moist and warm in summer creating conditions favourable for high pasture growth rates compared to north-facing aspects which are warmer in winter and often dry and hot in summer. (Betteridge et al., 2017).

Betteridge et al. (2017) investigated the influence of paddock topography on urination events in 20 3yr old sheep grazing a 2.8ha paddock. They reported that sheep moved an average of 2.6km a day, and spent little time on the top of, or the side of hills, with low slope and flat areas receiving the most urination events. The total minutes urinating was strongly correlated with elevation (r=0.88) and total minutes of urination was significantly influenced by elevation and aspect. Around sunrise, urine N concentration was highest and was probably concentrated around stock camps. Urine patches concentrated around stock camp compared to urine excreted across the paddock during grazing are probably the highest contributor of nitrogen loss. In addition, urine patch overlaps within stock camps have an increased risk of N emissions (Betteridge et al., 2010).

1.3.3.2 Stocking density

In New Zealand, the average sheep farm varies in size relative to soil productivity and management decisions. On the most productive soils, farm size fluctuates around 200ha, in hill areas up to 650ha, and in high-altitude areas they can be greater than 1000ha (Gillingham & Thorrold, 2000). Of the 7.1 million ha of land used for sheep and beef farming, the average stocking rates is approximately 9.4 stock units (SU) per ha. On hill land, this can differ from 5-20 SU/ha and for short, high intensity grazing periods a mob may reach 1200 SU/ha. The deposition of urine and faeces and the mechanical effects of hooves affect plant cover and diversity (Bilotta et al., 2007; Savadogo et al., 2007). The consequences of animal trampling depend on the stocking rate, phenological status of vegetation and soil texture and moisture. Grazing activities generally increase P loss in runoff from pastures and tends to increase with greater stocking densities (Hooda et al., 2000). Grazing distribution has been shown to change in response to stocking rate with Merino wether hoggets in a 16ha paddock with a steep (>30°) slope showing less variation in grazing occupancy at 4.08SU/hectare, compared with 1.91 and 2.98 stock units/ha (Thorrold et al., 1985). Stocking rate did not affect the resting distribution, but a higher distribution of excreta was observed increased stocking rates. Similarly, Olsen-P levels at 4.08SU/hectare were 3 to 12 test units higher at 1.91 SU/hectare ($p < 0.05$). The distribution pattern of excreta of grazing sheep might be influenced more by fluctuations in residual herbage mass than by intensity of grazing. Livestock play an important role in the nutrient cycles of a farm. However sheep utilise a small proportion of the nutrients they digest and approximately 60-99% of N, P, K, S, Ca and Mg are excreted (Williams & Haynes, 1990). Heavily grazed pastures encourage sheep to graze previously avoided urination and excretion sites (Forbes & Hodgson, 1985; Gonyou, 1984). Further deposition of urine and faeces on these sites results in additional nutrient loading that is likely to exceed plant and soil capacity promoting nutrient loss. Increased stocking rates and high intensity grazing is likely to result in proportionately greater environmental impacts by increasing the quantity of nutrients entering, recycling and leaving the system.

1.3.3.3 Riparian Zones

Riparian buffer strips have been shown to be an effective means of reducing sediment, nutrient, and pathogen transport into waterways (Burns & Nguyen, 2002; Gillingham & Thorrold, 2000; Stutter et al., 2012). In New Zealand, sheep generally graze outdoors year-round, increasing the excreta transported by surface and subsurface run-off to receiving waterways (Burns & Nguyen, 2002). The erosion of tracks and raceways, hillslope (sheet) erosion and stock damage to stream banks are critical factors that increase pollutant loads in streams (Collins et al., 2007; Parkyn, 2004). Waterways draining from improved pasture have significantly lower invertebrate community biomass and diversity (Death et al., 2018; Williamson et al., 1992). The protection of riparian margins by fencing is now widely recognised as a priority consideration for livestock farming systems due to the beneficial effects it has on stream bed and bank stability and the prevention of direct deposition of animal excreta into or near water (McKergow et al., 2016).

The advantage of monitoring the behaviour of sheep is that is can be studied non-invasively (Gougoulis et al., 2010). Scientific methods aim to assess experiences of sheep objectively through quantitative measurement of underlying behavioural and physiological processes (Wemelsfelder & Farish, 2004). Simultaneous measurements of physiology and behaviour can be used to identify emotional and physical responses of sheep to stimuli and link behavioural responses to stressors which are non-specific and consistent (Cockram, 2004).

1.4.0 Technology

1.4.1 GPS

A major benefit enabled by the Global Positioning System (GPS) technology enables animal behaviour within a spatial and temporal context on a landscape to be characterized (Brennan et al., 2021; Swain et al., 2011; Tomkiewicz et al., 2010). Monitoring sheep using GPS technology provides insight into how the animals behave in relation to environmental resources and their interaction with the natural ecosystem (Li et al., 2021; Plaza et al., 2020; Plaza et al., 2021). The positioning dataset can be managed using Geographical Information System (GIS) combined with aerial photographs, a reference map and with digital elevation models (Plaza et al., 2020; Plaza et al., 2021).

Spatial-temporal heterogeneity of vegetation exerts a strong influence on the behaviour of grazing animals, modifying their distribution therefore GPS data can provide insight into livestock utilisation of natural grazing areas (Plaza et al., 2020; Swain et al., 2011). GPS tracking devices on sheep can be used to define where animals congregate (stock camps) and the amount of excreta deposited in these regions (Betteridge et al., 2017). The intensity of stock interaction with their environment will influence their ecological impact. Flocks of sheep develop habits of movement that create tracks radiating from water sources and shade, generating a diverse array of impacts across the landscape (Norton et al., 2013). The creation of over and under grazed areas due to an uneven distribution of grazing can have immediate consequences on the distribution of natural resources.

Putfarken et al. (2008) used GPS receivers to analyse the differences in grazing-site selection and the effects of seasonality on grazing locations in cattle and sheep. Their results indicated sheep showed a preference for nutrient poor and dry habitats. Furthermore, they identified a link between sheep grazing sites located close to their sleeping area and that the spatial demands of sheep and cattle are complementary. To validate the data, they combined direct observation every 1 min over 6 days in spring and late autumn to verify the three behavioural categories inferred from the GPS records. This data was then analysed using GIS (ArcView 3.1, ESRI). Locational maps were created to show the presence of livestock in areas with different altitude, water sources, vegetation characteristics, and distance from fences and the sheep sleeping zone.

Visual distribution modelling of livestock across a landscape is beneficial for understanding the nutrient management requirements of a defined area. GPS units were attached to 14 sheep on a Norwegian military shooting range to assess the risk of Copper (Cu) and Lead (Pb) poisoning by monitoring their movements through contaminated zones (Johnsen et al., 2019). Similarly, custom-built GPS units were used to assess sheep urination frequency and urine distribution patterns in flat to moderately-rolling, to steep country in NZ (Betteridge et al., 2020). Information generated by understanding the implications of spatial preferences by sheep is essential when determining the impact, they have on their wider environment as well as the influence the environment has on sheep behaviour.

Limitations to the use of GPS in livestock monitoring are the availability of devices to monitor animal behaviour (Gaur et al., 2013). Paired with technical constraints, this inhibits the statistical vigour of experiments. Errors can be caused by low-battery conditions, power interrupts, signal loss, and multi-path interference effects (Swain et al., 2011; Webber et al., 2015). Thomas et al. (2008) noted the minimum velocity of sheep calculated from GPS receivers was around 0.1 km/h, inferring that some velocity data may be generated by GPS error, as it is probable that a sheep may be stationary. This may generate false location data. Using multiple data sets generated by monitoring movement is an accurate way to determine a sheep's spatial footprint. Combining GPS and inclinometers has been used to monitor sheep movement and orientation (Sheth et al., 2016). Geographic information system (GIS) allows for GPS data to be paired with numerous spatial parameters, a comparative advantage to direct observation (Plaza et al., 2021; Putfarken et al., 2008). A combination of high frequency accelerometers and GPS technology has potential for discriminating livestock behaviours by continuously monitoring an animal's movement and velocity (Brennan et al., 2021; Brown et al., 2013). By using a combination of spatial movement recording devices, the quality of data generated can be improved and thereby mitigate individual unit risk of inaccurate data collection.

1.4.2 Accelerometers

Labour costs and availability can inhibit the ability to observe sheep behaviour (Alvarenga et al., 2016; Brown et al., 2013; Decandia et al., 2018). Accelerometer technology provides the opportunity to monitor animal behaviour remotely over long periods of time without observer bias (Barwick et al., 2018; Brown et al., 2013). Accelerometers can measure both inertial and gravitational acceleration associated with animal movement on three axes (Brown et al., 2013; Fogarty et al., 2018).

Accelerometers have been used on sheep to quantify basic behaviours such as running and walking, lying, standing, grazing, ruminating, (Alvarenga et al., 2016; Barwick et al., 2018; Decandia et al., 2018; McLennan et al., 2015) and sheep posture and gait (Radeski & Ilieski, 2017). Miniaturization of acceleration sensors into three-axis microelectromechanical systems reduces the weight, size and power requirements of the devices allowing for easier, discrete mounting on animals (Alvarenga et al., 2016; Brown et al., 2013). Accelerometers can be attached to the animal with minimal obstruction or interfering with the natural movement of an animal (Marais et al., 2014). Halter mounted methods of accelerometer sensors deployment on sheep has been found to be acceptable in a research context (Barwick et al., 2018). Similarly, collar attached accelerometer systems have been used to classify activity levels and detect diurnal rhythms in sheep (Decandia et al., 2018).

When a sheep begins to accelerate, the change in the capacitance that exists between two accelerometers near one another other generates an electrical signal which can be developed into a data set that quantifies accelerative information along a defined axes (Barwick et al., 2018). The signal generated can indicate dynamic movement (inertial acceleration) and static acceleration (gravitational). Generally, information generated by tri-axial accelerometer devices consume very little digital memory space which is stored internally with the amount of data that can be collected limited by the size of the memory card and the frequency of measurements (Brown et al., 2013; Decandia et al., 2018). The sampling frequency of accelerometers usually ranges from 8 to 100 Hz. Sampling frequency can produce significant quantities of data which leads to a depletion of available memory space and increases battery consumption caused by transmitting and receiving data (Decandia et al., 2018). The impact of memory capacity and battery limitations may shorten experiment duration and data collection intervals which influences potential study designs (Fogarty et al., 2018). To date accelerometers have not been used to investigate the behaviour of sheep around waterways.

1.4.3 Cameras

Continuous observation of animal behavioural activities by direct human observation is time consuming and labour intensive (Barwick et al., 2018; Giovanetti et al., 2017). The use of cameras in pastoral systems has the potential to reduce the cost involved in human observation (Perry et al., 2010) and improve animal welfare surveillance by illustrating the physiological state of the animal together with environmental factors (Herlin et al., 2021). Understanding the conditions present, without human interference, will allow an accurate representation of the animal’s behaviour in response to the environment it is present in.

Most of the studies in the literature have examined animal behaviour during feeding, assessing the spatial density of a flock and determining activities during the different physiological stages of a sheep's lifespan. To my knowledge, there have been no studies using cameras to examine sheep behaviour around waterways. Langbein et al. (1998) used infrared cameras during the night and colour cameras during the day to record the behaviour of five pregnant Mouflon sheep females over a lambing season. Similarly, the use of cameras were used to assess desert bighorn sheep to determine an average size of the population (Perry et al., 2010) . Decandia et al. (2018) used a video camera equipped with an accelerometer positioned in a corner outside the paddock to record individual feeding behaviour of sheep. Walton et al. (2018) also used a combination of tri-axial accelerometers and a handheld video camera with a tripod to record sheep behavioural activities. Previous research highlights the opportunities for using remote cameras to record sheep movement around hill country waterways. As there will be minimal human disturbance to their behaviour, data can be recorded for several days at a time and linked to GPS movement to show their behaviour and activity around waterways and determine what influence a sheep's different behaviours have on the impact they cause water quality.

1.5 Conclusion

Sheep farming in New Zealand is entwined in our nations heritage and is critical for the economy and the farmers. Nearly forty percent (10.6 million ha) of New Zealand's total land area is used for sheep and beef farming (Maseyk et al., 2021). Water quality in New Zealand is a comprehensive and complex topic, with many opinions and regulations influencing its function in society but it is a well-documented fact that contamination of drinking water can come from agricultural activities (Richards et al., 2021). Water availability, however, is extremely important for animal health and production, and freedom from thirst is the first of the freedoms recommended by the Farm Animal Welfare Council (Jensen & Vestergaard, 2021). There is limited information known about the drinking behaviour of sheep (Jongman et al., 2008) or their behaviour in and around a free flowing stream. There is a further gap on the direct influence sheep have on hill country water quality. Information on how sheep behave and interact with a natural waterway is essential for safeguarding the management of our local resources and promoting a sheep farming system that optimises agroecological wellbeing and longevity. This research will be conducted across two seasonal trials and will utilise a combination of available technology to create a descriptive analysis of sheep behaviour and how they move around a paddock. This can be used to determine how they influence water quality.

Chapter 2 The interaction of ewes with a natural waterway in Summer and the impacts on water quality.

2.0 Abstract

Little is known about the drinking behaviour of sheep or how they interact with natural waterways within a paddock, despite the risks to water quality and possible legislation around stock exclusion. It was hypothesised that sheep behaviour around a natural waterway would vary with season. The objective of this study was to examine sheep behaviour in summer in the presence and absence of a water trough and their impact on stream water quality. Mixed age ewes (n=40) were randomly allocated an accelerometer (n=40) and GPS unit (n=20). The trial used a crossover design whereby ewes had access to a trough for one week and access restricted for the second week. Water samples were collected fir two days each week from the stream inflow and outflow to the trial site. Water samples were assessed for total nitrogen, ammonium, nitrate, dissolved phosphorus, total phosphorus, suspended sediment, and *E. coli*. During the study period there were no recorded observations where sheep excreted or urinated directly into the stream zone and two occasions where sheep were recorded to urinate within 3m of the stream (the stream zone). When sheep had access to a trough, they did not drink from the stream but were observed to drink from the stream when access to the trough was restricted, although, the duration of events did not differ. Sheep spent more time grazing the flatter areas of the paddock near the stream zone and the water trough. Measures of water quality were elevated when sheep had unrestricted access to a trough, however, this was associated with a rainfall event on that day. During the sampling day when rainfall was recorded the mean *E. coli* concentration was 4350 cfu/100ml which exceeded the freshwater recreation Microbial Assessment Category water quality guideline D grade threshold of >550 MPN/100ml. Mean total nitrogen concentrations were 2.12 L^{-1} which was below the threshold of tolerable concentrations for a cool wet hill recommended by the Australian and New Zealand Guidelines for Marine and Freshwater Quality which is 2.38 mg L^{-1}. These elevated concentrations were likely a result of a build-up of nitrogen within the soil and *E. coli* on the soil surface over summer which was then transported to the stream in surface runoff. Removing access to a water trough did not directly influence sheep behaviour during summer in the Manawatu and had minimal impact on stream water quality.

2.1 Introduction

Changes to stock exclusion regulations were introduced in New Zealand on 3rd of August 2020 after a revision of the Resource Management Act (RMA). The revision required that farmed cattle, deer and pigs be excluded from waterways more than 1 m wide using a setback of 3 m (Resource Management Act, 2020). This requirement is likely to add substantial cost to hill country farming enterprises in terms of fencing and the installation of reticulated water systems. Currently, sheep do not require exclusion, however, more information is needed about the behaviour of sheep in New Zealand hill country particularly around natural waterways to determine their impact on water quality.

In the Manawatu region of New Zealand mean monthly air temperatures in summer range between 15 and 20°C (Choudhary et al., 2002). Pasture production in this region is characterised by low yields during summer resulting from a soil moisture deficit (Causley, 1990). There are an estimated 4500 sheep and beef farms across New Zealand with rolling (8-20°) to steep (>21°) country accounting for 32% and 40% of the land area, respectively (Beef and Lamb, 2020b). Hill country sheep farms in New Zealand generally have poor water reticulation because of their contour and topography, resulting in sheep accessing drinking water primarily from dams and streams (Donnison et al., 2004). Associated with increased temperature and sunlight intensity, sheep may choose to seek cooler areas associated with waterways, as well as having a water source readily available. Riparian areas (stream zones) provide water, shade, and high quality forage (Bailey & Brown, 2011). In addition, the stream zone may have lush grass as a result of readily available water. Combined, these factors may increase the risk of sheep entering waterways and thus impacting water quality.

Advances in technology have enabled the accurate monitoring of sheep behaviour in pastoral systems. Through the use of activity monitoring technologies such as GPS tracking devices, motion activated cameras and triaxial accelerometers data can be generated to determine the behaviour of the sheep, its proximity to the waterway and their distribution across a defined area.

The objective of the current study was to monitor sheep behaviour, spatial distribution, and proximity to a natural stream when provided access or restricted from accessing a reticulated water trough and to determine their impact on stream water quality. We hypothesized that when sheep had unrestricted access to a drinking trough in summer, they would not drink from the natural waterway and therefore have no effect on water quality.

2.2 Methods

All the procedures in this study were carried out with the approval of the Massey University Animal Ethics Committee (MUAEC 19/62). The study was conducted at Massey University's hill country farm, Tuapaka, located approximately 15 km north-east of Palmerston North (40.3346° S, 175.7316° E). Mixed-age ewes (n=40) were managed in a 2.94 ha paddock that contained a discrete natural stream. The stream zone area (3m either side of the stream), accounted for 0.23ha of the 2.94 ha (7.9%) of the total paddock area. Sheep were continuously stocked on a perennial ryegrass pasture in which masses were maintained above 1000 kg DM/ha. The stream was classified as a sixth-order stream (based on high resolution 1 m LiDAR digital elevation data; Fig 1.) (LINZ, 2021). The stream was 233 m long, 1 m wide and less than 30 cm deep (Fig. 2).

Figure 1 Slope contour (in degrees) of the study site on Tuapaka farm (dark green indicate a slope of 0-3°, mid green 3-7°, light green 7-18°, yellow 16-20°, light brown 20-25°, mid-brown 25-35 and dark brown 35-75°). Slope categories accessed from Lynn et al. (2009).

Figure 2 Study site showing the stream (blue line), stream zone (3m each side of the stream; green shading) and location of the inflow and outflow culverts (orange rectangle).

Video surveillance cameras (numbered 1 to 14) were attached to metal stakes placed at intervals of between 5 to 15 meters along the entire length of the waterway with an additional camera (camera 15) placed near the single water trough in the paddock (Fig 3.). The cameras were a mix of Moultrie (Model MCG-13297, Birmingham, USA), Bushnell (Model 119736, Kansas City, USA) and TechView (Model QC8027, Rydalmere, Australia).

Figure 3 Study site showing the camera locations along the stream. Each camera was attached to a metal stake and was paired with an accelerometer.

2.2.1 Study design

The study used a crossover design whereby sheep had unrestricted access to a water trough for the first week of the study (study days 1 to 7, D1 to D7) followed by a period of restricted access when the trough was covered (D8 to D14). During each treatment period, video camera footage was used to determine sheep behaviours in the stream zone and interaction with the stream. In addition, GPS location data and accelerometer proximity were used to determine the duration that sheep spent near the stream. During the final two days of each week (D6, D7, D13, D14), stream water samples were collected to determine the concentration of *E. coli*, nitrogen, phosphorus and suspended sediment.

2.2.2 Climate

Climate data was measured using a Davis Vantage Pro 2 6322C weather station (Davis Instruments, Hayward, California, USA). The weather station measured rainfall, temperature, solar radiation, wind speed, barometric pressure and humidity (Davis Instruments, 2014). Minimum and maximum temperatures were defined as the highest and lowest recorded temperature during each 24hr period. Precipitation was defined as accumulated rainfall collected every 20 to 24 seconds and averaged for each 24 hr period (Brett, P., per comm).

2.2.3 Animal measures

Sheep live weight was recorded on D1 and D14 using a purpose-built weigh crate (XR5000, Tru-test and Datamars, Auckland, New Zealand). Sheep were also body condition scored by an experienced technician at each weighing event using a 0 to 5 scale (Kenyon et al., 2014).

Each sheep (n = 40) was fitted with an accelerometer (WGT3X-BT, Actigraph, Pensacola, Fl, USA) attached to a halter using cable ties. Sheep location relative to the camera positions was determined using the Bluetooth® proximity feature of the triaxial accelerometer. The accelerometers that were attached to the halter were programmed to be a beacon and broadcast a continuous signal of the of the serial number of the device. Accelerometers were also placed at sheep head height on the metal stake at each camera location (n=15) which were programmed to be a receiver. Receivers searched for beacon signals once per minute which, if detected, were stored as a minute-by-minute log of the received signal strength indicator (RSSI). The accelerometers were wrapped in a silicone self-adhesive tape (Tape-it, Calibre, Concord, Canada) to provide additional waterproofing. Accelerometers were time synchronised with video cameras to ensure that video recordings could be matched with accelerometer signals.

GPS units were used to record the spatial location sheep within the study site. GPS units were constructed by DataCarter (www.datacarter.co.nz) and contained a u-blox 8® GNSS chipset (www.u-blox.com). Twenty sheep (n = 20) were randomly allocated to wear a GPS collar for two days of each week of the study (D1-3 and D7-10). GPS units were powered using Tadrian™ lithium inorganic 3.6volt battery (model TL-5930r) and placed into a waterproof moulded case (140g +/- 3%) which was attached to a neck collar.

Each sheep was also fitted with a plastic collar that contained a unique colour and number combination to allow identification of individual sheep from the video camera footage. In addition, the accelerometer identification number was painted onto the flank of the sheep using coloured stock spray (Sprayline®, Donaghys, Christchurch, New Zealand)

2.2.4 Pasture Sampling

Pasture samples were collected on D2, D7 and D12 to determine the pasture moisture content. Samples were collected randomly from within three locations; flat grazing areas (top), sloped sides of the gully (middle) and grazing areas beside the stream (bottom). Approximately 55 to 75 g of fresh pasture was collected from each sampling location by hand plucking in order to imitate sheep grazing. The sample was weighed prior to drying and then placed in a 70°C oven for a minimum of 4 days. Once dried, the sample was re-weighed and moisture percentage determined by dividing the dry weight by the wet weight and multiplying by 100.

Pasture mass (kg DM/ha) was estimated using a folding pasture plate meter (Genquip, Fielding, New Zealand) on D3, D6, D7 and D12. A transect line with 100 measurements was taken twice across each flat side of the trial paddock.

2.2.5 Stream flow rate and water quality measures

A water sample of 1 litre was collected simultaneously every hour from both the upstream and downstream sections of the stream between 08:30 and 13:30 on D6, D7, D13 and D14.

Stream inflow and outflow flow rates were determined at the same time as water quality samples were collected, by measuring the volume of water collected in a 15 L bucket over a set period of time using a stopwatch. Flow rate was calculated as the mean of three measurements. *E coli* water samples were collected using a sterile 120ml YT Lab-serv container. Samples were then stored in an insulated box and couriered on ice to a laboratory that same day, to be analysed the following day.

Water samples for determination of nitrate-N and ammonium concentrations were prepared for storage at -20°C by filtering the 1 litre sample to <0.45μm on the same day of collection within one hour of the last sample being taken. Samples were analysed using colourmetric analysis by adding a visible dye. Red azo was added to samples analysed for nitrate-N and phenol Prussian blue for ammonium. Samples were analysed using an auto analyser (Pulse Instrumentation Ltd, Saskatoon, Canada) with a detection limit of 0.25 mg/L.

Total Nitrogen samples were frozen on the same day of collection within one hour of the last sample being taken and were stored at -20°C. Samples were analysed by first digesting the sample with persulphate (Hosomi & Sudo, 1986) and then analysing with an auto analyser (Pulse Instrumentation Ltd, Saskatoon, Canada). The detection limit was 0.25 mg/L.

Water samples for dissolved reactive P were filtered to <0.45μm on the same day of collection within one hour of the last sample being taken and then frozen at -20°C. Samples were analysed using molybdenum blue colourimetry and DRP concentration measured using flow injection analysis (APHA 4500-P G (modified) 23rd ed. 2017) which has a detection limit of 0.004 mg/L.

Samples for determination of total P were frozen on the same day of collection within one hour of the last sample being taken and were stored at -20°C. Total P was determined using an acid persulphate digestion and automated ascorbic acid colorimetry via flow injection analysis (APHA 4500-P H (modified) 23rd ed. 2017) with a detection limit of 0.002 mg/L. Dissolved reactive P samples were contaminated and could not be analysed.

Suspended sediment was determined by filtering a known volume of sample (~1 l) through a pre-weighed Whatman 110mm glass microfibre 1.2µm filter (CAT No.1822-110, Little Chalfont, United Kingdom). Each filter paper was then oven dried for 12hrs at 105°C and then re-weighed to determine sediment mass.

Contaminant loads for all water quality parameters were calculated by multiplying the concentration by the stream flow rate at the time of sampling and expressing contaminant load on a weight per time basis (mg s^{-1}).

2.2.6 Behavioural Analysis

Behaviour of the study sheep was observed from video footage captured from 15 video cameras located along the stream and at the water trough (Fig. 3). The behaviours of interest related to grazing and water intake within the stream zone (3m either side of the stream; Table 1). Observations were coded using BORIS (Friard & Gamba, 2016) a behaviour recording software. BORIS was used to record the frequency and duration of each behaviour observed from the video recordings. All video cameras were motion activated and programmed to record for 30 seconds once triggered. If movement was detected 10 seconds after the end of a recording, another 30 seconds was recorded and so on, until no movement was detected. Behaviours observed in video footage that was recorded within 1 minute of the previous video was classified as ongoing and allowed the creation of behaviour bout durations.

2.2.7 Proximity

Data from the accelerometers was downloaded using the proprietary software Actilife®. Proximity of the beacons to the receiver was determined using the equation received signal strength indicator (RSSI) = $-65.5817 + 20 \log_{10}$ distance (m). This equation represents the signal gain and loss of hardware estimated from measured RSSI values of known distances in the range of 0.5 to 12 m (Sohi et al., 2017). In this study the distance was set at 3 metres.

Table 3. Ethogram of sheep behaviour coded from video footage recorded throughout the study period.

Behaviour	Code	Description
Stationary	P	Sheep was inactive either standing or sitting. Includes sheep that were ruminating (regurgitation; re-chewing and re-swallowing) or scratching. Standing was defined as all four feet on the ground and no locomotion. Sitting was defined as at least 50% of body or side in contact with the ground and not being supported by all 4 feet
Grazing	E	Sheep harvesting vegetation from the ground. Could be standing still or walking with muzzle close to the grass (i.e. head is below shoulders)
Laying	L	Sheep lying, stationary on surface. Not supported by all 4 feet
Walking	W	Moving from one point to another, did not include walking while grazing
Drink	D	Animal consumed water and had lips in contact with stream water for more than 5 seconds
Sniff	S	Moved muzzle towards water and inhaled but did not drink
Stream Interaction	I	Sheep was within 1m of the stream and engaged in other behaviours
Walk in the stream	A	Sheep stepped in the stream without drinking water
Other	O	Sheep performed other behaviours, such as, play, fight, urinating or excreting

2.2.8 GPS

GPS longitude and latitude data was recorded in GMT time which was converted to New Zealand daylight saving time. GPS data was trimmed to create a data set that was 48 hours long with all data points registered within the paddock boundaries. Any data points that provided inadequate information, such as a latitude or longitudinal reading that was not consistent with the study location, or data points recorded from 3 satellites or less was discarded.

Coordinates created from the GPS units were analysed using GIS ArcPro (Esri, 2021). The plots were clipped to the paddock boundary so that no GPS coordinates were included that were not consistent with the study site. Hotspot geoprocessing programmes were used to create visual representations of sheep spatial location and movement within the study site. Maps of the entire study site and the stream zone (3m each side of the stream bed) were created for each treatment period.

2.2.9 Statistical Analysis

Pasture moisture and mass results were tested for normality using the students t-test ($p < 0.01$) and analysed using SAS (SAS Institute, SAS 9.4. Cary, NC, USA). Bottom pasture sample for moisture testing on the 12th February (D3) was invalid due to contamination of the sample with foreign matter.

The total number of behaviour events and the total duration were tested for normality (students t test) and were compared between treatments and camera locations. Due to SD storage corruption no recordings were captured from Camera 9. The duration and number of events for all behaviours (stationary, grazing, laying, walking, drinking, sniffing, stream interaction, walking in the stream and other) observed during the study period were not normally distributed ($p < 0.001$). The non-parametric Kruskal–Wallis test was then used to identify any differences between variables.

Accelerometer data was not recorded during the second week (the trough restriction period) due to battery failure. The proximity data (per sheep minute) was summarised using Microsoft Excel (2018) using a pivot table. Proximity was summarised as the duration per hour that each sheep was detected within 3 m of each camera location and was transformed using a $\log_{10}$ transformation, however, was unable to normalise the data distribution, but allowed for improved visual inspection of the data. Box plots of the proximity data were generated using SPSS (IBM SPSS Statistics 27, New York, United States of America). Proximity data generated was examined using the non-parametric Kruskal-Wallis test.

GPS data were analysed using an optimised hotspot analysis (Getis-Ord GI*) to examine the effect of each feature within the context of neighbouring features (Esri, 2021). A feature is classified as a data point generated from longitudinal and latitudinal information created by each sheep wearing a GPS unit. To be a statistically significant hotspot, a feature had to have more points per area (high value) than the average for the paddock and be surrounded by other high values. Cold spot represented an area that received significantly less sheep location clusters (low value) compared to the expected number given a random distribution of sheep clusters. The local sum for a feature and its neighbours was compared proportionally to the sum of all features (total GPS points created within the paddock area).

The frequency of GPS locations that were identified in the stream zone and in the reminder of the paddock was determined for each treatment period. The frequency data was then analysed using a Pearson's chi-squared test to determine whether there was statistically significant differences between the expected and observed frequencies of the GPS data location information within each area.

Water sample data were analysed using SAS. All water quality metrics; flowrate, suspended sediment, total nitrogen, ammonium, nitrate, total phosphorus and *E. Coli* were not normally distributed (students t test, $p < 0.001$). Concentrations of ammonium and nitrate that were below the detection limit were given a value of the method detection limit divided by the square root of two according to the method of Sandford et al. (1993). This approach was only used when < 20% of values for an individual parameter were below the detection limit. If more than 20% of the data was below the detectable limit, the data was not analysed. Nonparametric, univariate analyses (Kruskal-Wallace) were used to determine differences between treatments (unrestricted trough access, restricted trough access), samplings days within the treatments and the inflow and outflow sampling locations. Correlations were calculated using SAS between suspended sediment, *E. Coli* and total phosphorus. Data from non-parametric tests are presented as the means, medians and interquartile range to aid in comparison with literature and New Zealand industry standard guideline.

2.3 Results

2.3.1 Climate

During the experimental period, 2.2 mm of rainfall fell on D1 (10th February 2021) and 24.5 mm D7. Daily maximum temperatures ranged from 17.9-27.8°C and minimum temperatures varied between 5.1-17.2°C.

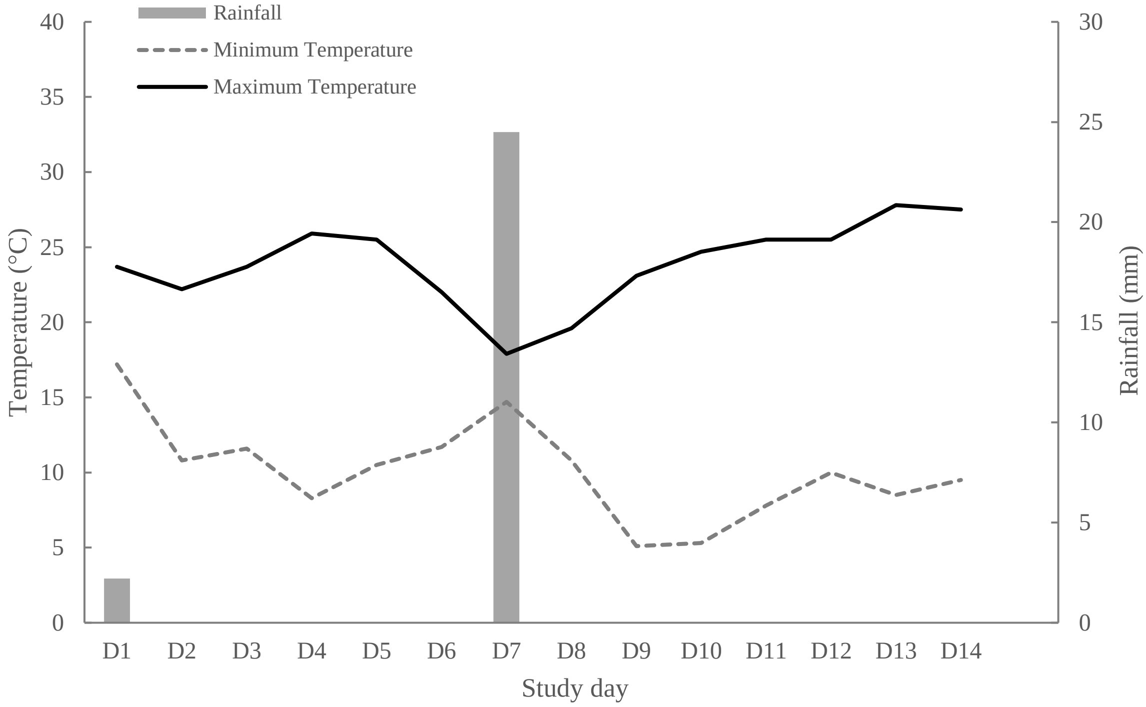

Figure 4 Daily rainfall (mm) and temperature (°C) recorded during the study period. Water sampling was carried out on day D6 and D7 (12th and 13th February; unrestricted trough access) and on D13 and D14 (19th and 20th February; restricted trough access).

2.3.2 Pasture Analysis

Pasture mass was not different between each day sampled ($p = 0.2615$) or between sampling locations ($p = 0.7728$). Pasture moisture was different between study days ($p = 0.0439$) but was not different between sampling locations ($p = 0.4054$).

Table 4 Pasture mass (kg DM/ha) and moisture content (%) recorded during the summer observation period. Pasture masses were determined in the northern flat area of the paddock (Top) and the western flat area (bottom). Pasture moisture samples were collected from the top of the paddock (Top), the sloped area of the gully (middle) and the areas adjacent to the stream and at the bottom of the gully (bottom).

Study day	Date	Plot	Mean
Pasture Mass (kg DM/ha) [1]			
D3	12/02/21	Top	1990.14
D3	12/02/21	Bottom	2274.54
D6	15/02/21	Top	2130.76
D6	15/02/21	Bottom	2190.8
D7	16/02/21	Top	2266.64
D7	16/02/21	Bottom	2088.1
D12	22/02/21	Top	1896.92
D12	22/02/21	Bottom	1854.26
Moisture content (%) [2]			
D3	12/02/2021	Top	71.70%
D3	12/02/2021	Mid	71.83%
D6	15/02/2021	Top	69.34%
D6	15/02/2021	Middle	68.62%
D6	15/02/2021	Bottom	65.88%
D12	22/02/2021	Top	62.05%
D12	22/02/2021	Middle	59.44%
D12	22/02/2021	Bottom	53.52%

2.3.3 Sheep Behaviour

Of all the behaviours recorded eight sheep each contributed more than 4% each which accounted for 52% of the behaviours. There were 16 sheep that each contributed between 1-3%, which accounted for 29% of the total behaviours. Finally, there were 14 sheep that contributed less than 1% each, contributing a total of 7% of behaviours. There were two sheep that were not observed to enter the stream zone during the entire study period. There were no recorded instances of sheep excreting or urinating into the stream itself and two observations of a sheep urinating within the stream zone. No sheep were seen to excrete within the stream zone.

The camera located as position 1, located at the outflow water recording site behind the northern most culvert, recorded the highest total number of observations during the study period (n=250). The longest median grazing duration was recorded by the camera at location 7 (Table 5) which was due to an individual sheep being recorded for several consecutive recordings and performing the same behaviour which was then classed as one bout.

Sheep were recorded to drink on 47 occasions with a mean duration of 12.7 seconds (Table 6). Of those ewes observed to drink from the stream, 13 drank only once and five drank on between 2 and 5 occasions and 20 were not recorded to drink at any time. The frequency of drinking behaviours differed between camera locations ($p = 0.017$). There was a tendency for the duration of drinking bouts to differ between camera locations ($p = 0.086$). Sheep were observed to drink more often when access to the trough was restricted than unrestricted ($p = 0.007$), however, the duration of drinking bouts did not differ ($p = 0.304$). There was no effect of access to the water trough on the total duration of drinking events ($p = 0.316$).

Sheep were observed to sniff the water in the stream on 45 occasions during the study period with a mean duration of 6.6 seconds (Table 6). There was no difference in the total duration sheep spent sniffing ($p = 0.066$) or the number of sniffing events ($p = 0.749$) between the restricted and unrestricted treatment periods. Sniffing was a relatively short duration behaviour (<10 seconds) and usually preceded another behaviour, either walking in the stream or commencing grazing in the stream zone.

During the study period, sheep were recorded to interact with the stream (exhibit behaviours within 1m of the flowing stream water) on 206 occasions with a mean duration of 49.1 seconds. Total duration of stream interaction events did not differ between treatments ($p = 0.072$) but there was a difference in the number of events ($p = 0.007$).

Sheep were observed to walk in the stream on 100 occasions during the summer period with a mean duration of 52.4 seconds. There were eight sheep that were not observed to walk in the stream, fourteen sheep that walked in the stream more than once and four sheep on more than five occasions. The median number of events recorded were one, with an interquartile range of 1 to 2. There was no difference between treatments in the total duration of sheep walking in the stream ($p = 0.495$) but the number of events differed between trough access periods ($p = 0.007$).

Table 5 The number of sheep (n) and the median duration (s; with interquartile range in parentheses) that sheep were observed to show each behaviour (walk, graze, be stationary, lay down and other) at each camera location.

Camera	**Sheep behaviour durations (s)**									
	n	**Walking**ȣ	**n**	**Grazing**ɿ	**n**	**Stationary**Д	**n**	**Laying**ф	**n**	**Other**ȝ
1	74	23 (13.7-45.2)	62	14 (7.7-26.6)	24	11 (4.4-19.0)	1	1 2.6 (2.6-2.6)	1	1.3 (1.3-1.3)
2	6	8.5 (5.57-12.4)	11	14.0 (13.6-23.8)	1	3.6 (3.6-3.6)	-	-	-	-
3	13	7.4 (5.0-9.9)	34	51 (31.0-91.4)	5	4.7 (4.5-11.5)	-	-	-	-
4	31	9.4 (6.9-16.5)	62	28 (14.7-48.3)	30	10 (4.7-19.2)	3	165 (120-296.3)	4	3.2 (2.2-9.0)
5	8	9.9 (5.7-12.1)	17	36 (29.6-58.7)	8	7.3 (3.2-9.7)	-	-	-	-
6	10	6.2 (2.7-11.1)	27	61 (18.1-87.0)	5	2.8 (2.12-3.9)	-	-	-	-
7	6	17 (11.3-17.8)	43	133 (66.9-379.2)	2	4.9 (4.1-5.9)	-	-	1	10 (10.8-10.8)
8	22	4.7 (2.92-11.1)	51	62 (30.3-168.8)	9	5.3 (4.0-12.1)	-	-	-	-
10	18	7.6 (4.3-11.0)	44	57 (17-113.4)	6	4.8 (3.6-10.2)	1	319 (319-319)	-	-
11	19	4.2 (2.9-5.3)	36	42 (29.9-63.0)	9	5.3 (4.0-9.8)	-	-	-	-
12	12	8.3 (4.3-14.3)	28	102 (45.6-203.9)	9	14 (9.7-27.5)	-	-	-	-
13	18	4.1 (2.3-6.4)	57	49 (29.8-121.2)	10	2.4 (1.8-5.6)	-	-	1	8.5 (8.5-8.5)
14	9	6.6 (3.9-10.6)	18	31 (13-62)	6	13 (7.4-108.8)	1	31 (31.6-31.6)	-	-

– indicates that no sheep were observed to show the behaviour in video footage recorded at the camera location. ȣ Motion from one point to another, ɿ Harvesting vegetation from the ground, Д Inactive either standing or sitting, ф Lying on a surface, ȝ Any other behaviour not defined.

Table 6 The number of sheep (n) and the median duration (s; with interquartile range in parentheses) that each water related behaviour was observed (drink, sniff, interact with stream and walk in stream) at each camera location.

Camera	**Sheep behaviour durations (s)**							
	n	**Drinking**$^{\phi}$	**n**	**Sniff**$^{¥}$	**n**	**Stream Interaction**§	**n**	**Walk in stream**
1	-	-	-	-	30	19 (10.4-30.14)	28	11 (8.48-32.28)
2	-	-	5	8.2 (5.63-14.92)	-	-	-	-
3	-	-	-	-	19	21 (11.1-40.85)	22	16 (14.3-29.3)
4	4	4.6 (3.42-5.2)	3	6.2 (4.92-15.81)	29	14 (10.1-29.72)	5	11 (1.67-12.1)
5	-	-	-	-	6	24 (5.14-28.05)	2	186 (53.3-318.9)
6	9	16.6 (4.17 - 21.05)	4	6.6 (4.28-17.54)	20	21 (9.38-40.5)	24	21 (13.8-103)
7	4	26.0 (15.95 -40.95)	1	7.7 (7.73-7.73)	7	24 (20.8-124.6)	22	82 (32.5-130.5)
8	7	6.2 (3.39-18.38)	7	3.2 (2.62-12.6)	20	12 (8.22-29.41)	19	15 (5.49-33.58)
10	-	-	-	-	-	-	10	13 (10.4-41.74)
11	6	7.8(3.39-18.38)	5	3.2 (2.62-3.619)	7	27 (8.6-28.44)	17	16 (5.49-31.08)
12	8	12.0 (6.36-22.9)	7	2.4 (1.97-9.199)	16	27 (19.7-60.07)	12	32 (14.7-58.84)
13	5	9.3 (9.23-18.63)	12	3.2 (1.63-6.09)	24	14 (8.61-33.1)	20	24 (8.75-68.25)
14	4	5.8 (1.17-13.49)	1	3.9 (3.91-3.91)	10	18 (12.3-31.94)	8	9.8 (3.17-81.4)

– indicates that no sheep were observed to show the behaviour in video footage recorded at the camera location. ϕ = Drinking from the stream, ¥ = Muzzle toward water and inhaled, § = Within 1m of the stream engaged in other behaviours, Ӝ = In the stream, moving or stationary without drinking.

2.3.4 Proximity to camera locations

On D1 and 2, sheep were detected near the surveillance cameras for less than an hour (Fig 5). The greatest median duration any sheep spent within 3 m of the surveillance cameras occurred on D4 and decreased on D7.

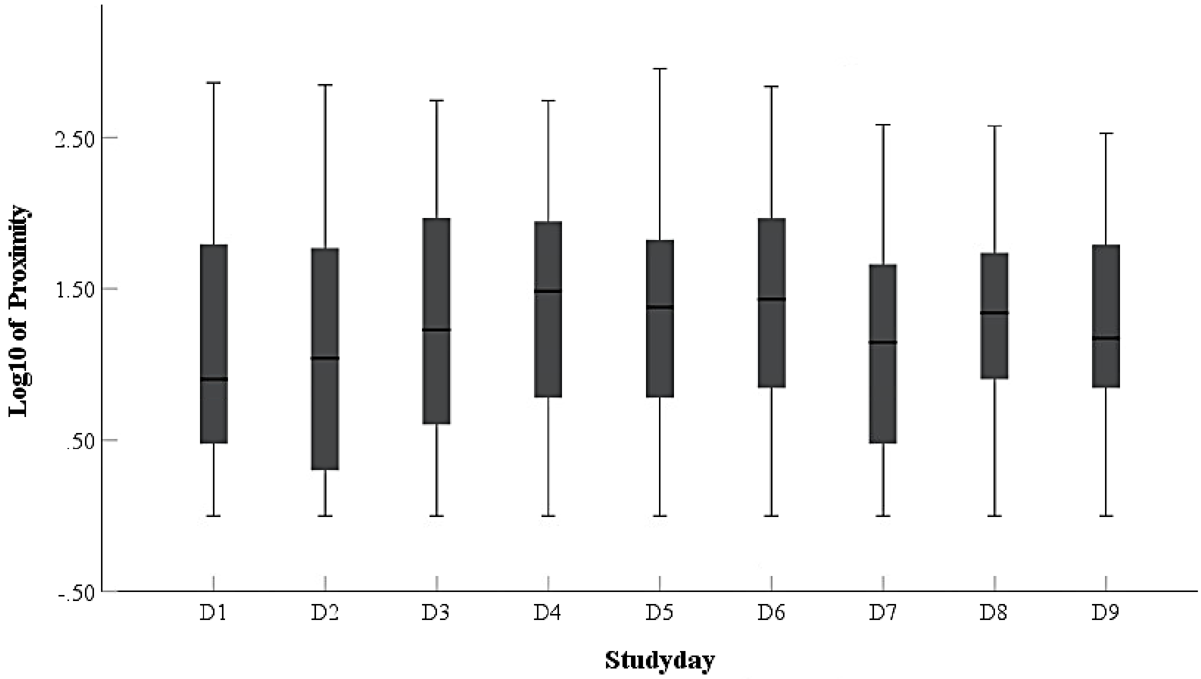

***Figure 5** Log_{10} transformation of the duration sheep were in proximity of camera locations (within 3m) in minutes per day during the study period. Sheep had unrestricted access to the trough between D1 and D7 and were restricted from accessing the trough between the D8 and 9. Due to battery failure data was not recorded between D10 and 14.*

Camera location influenced the duration that sheep were in proximity. Sheep were detected for greater durations at the downstream cameras (1-5; Fig 7.) than those upstream. Sheep were detected within 3m of Camera 1 for a median 822.5 sheep minutes throughout the entire duration of the experiment. Cameras 1, 3 and 11 had longer durations with sheep in proximity than the remainder of the cameras ($p > 0.05$). The middle zone had the least activity with Camera 6 detecting sheep for a median of 95.5 sheep minutes and Camera 7 for 97.5 minutes. Cameras 6, 7, 8 and 10 had less sheep proximity duration than the rest of the cameras ($p > 0.05$). Camera 11 detected sheep for a median of 650.5 sheep minutes. Camera 15, which as located next to the water trough showed the highest duration of sheep in proximity throughout the study.

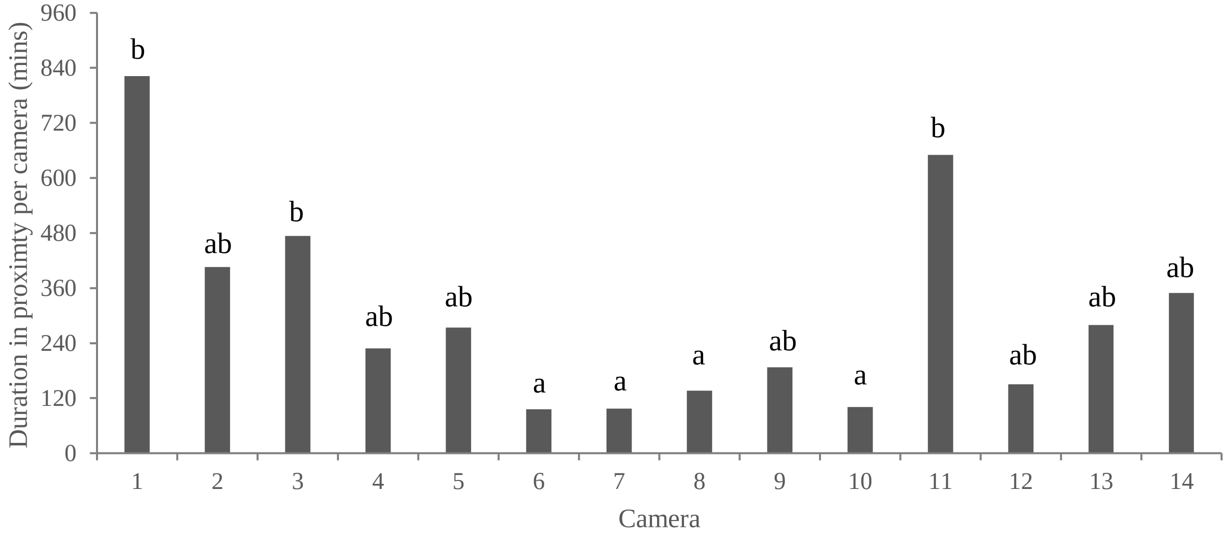

Figure 6 Median duration (in sheep minutes) that sheep were detected within 3m of each camera location during the observation period. [a,b] Bars with different superscripts are significantly different (p<0.05).

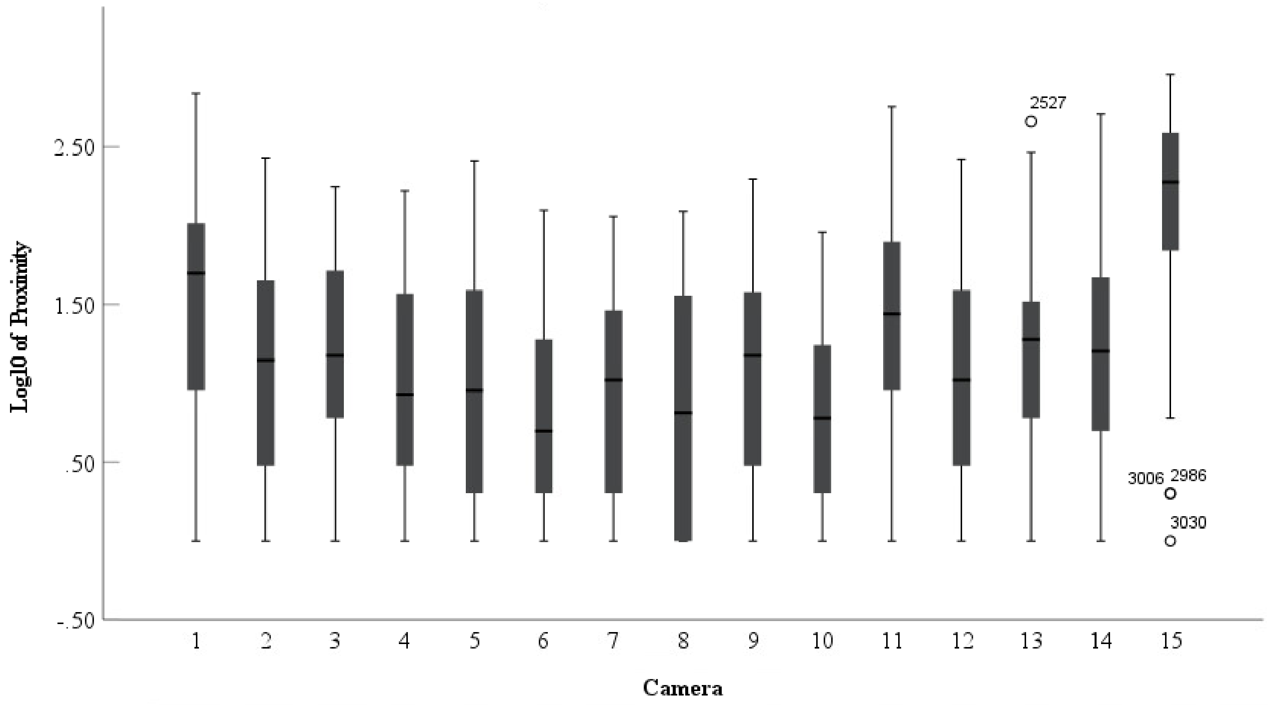

Figure 7 Log_{10} transformed proximity duration (sheep minutes per day) that sheep were detected within 3m of each camera location during the study. ° indicates values outside the inter quartile range.

Sheep were detected within 3m of camera locations for shorter durations ($p < 0.05$) between 12:00 and 06:00 than during daylight hours (Fig 7). Proximity durations between 8.00 and 15.00 did not differ ($p < 0.05$). There is a gradual decline in proximity duration between 7.00 and 12.00 while the early morning (3.00-5.00) and evening (20.00-22.00) showed increased proximity durations.

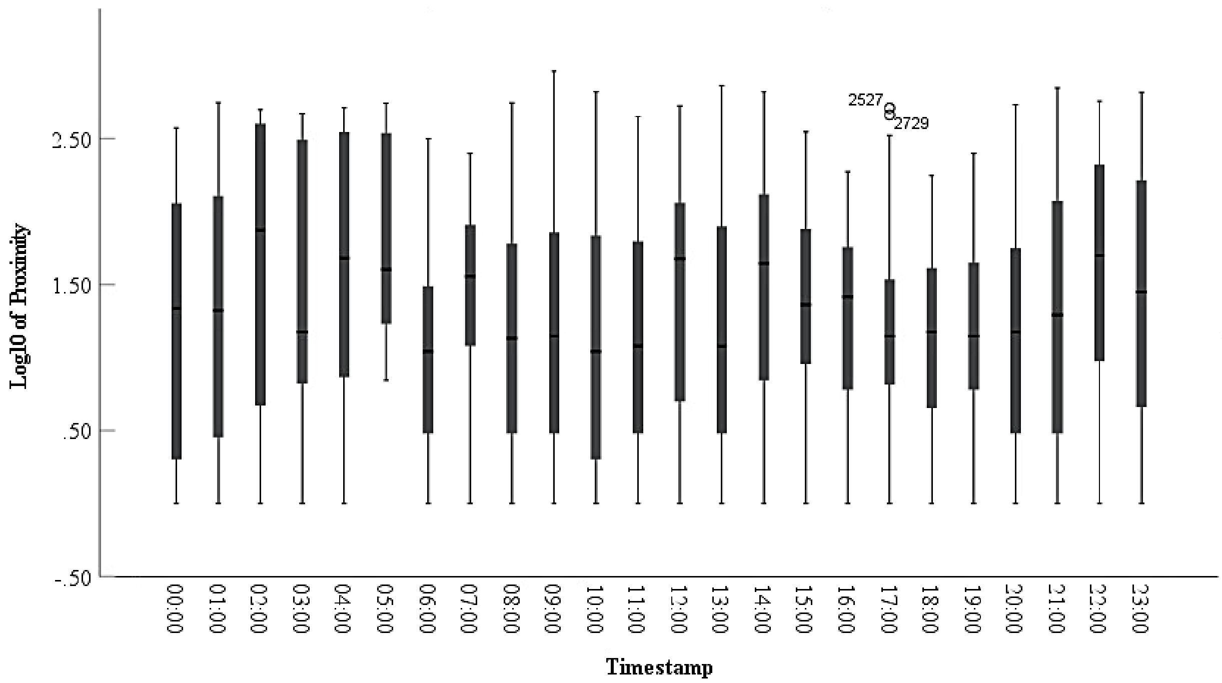

Figure 8 Log_{10} transformation of average proximity duration (sheep minutes) that sheep were detected within 3m of any camera location during the summer observation period per hour of the day.

2.3.5 GPS locations

During the period of unrestricted access to the water trough, there were 310 GPS locations recorded within the stream zone (0.63%) and 48,983 in the remainder of the paddock (99.37%). During the period of restricted access to the trough, there were 1,388 GPS locations within the stream zone (2.97%) and 46,725 in the remainder of the paddock (97.03%). There was no difference in the observed and expected number of GPS data points identified within the stream zone ($p < 0.01$).

When the sheep had unrestricted access to the trough, the area surrounding the trough showed a significant hotspot ($p< 0.05$) (Fig 9A). This area was flat with a slope of 0 to 3° (Fig 1). When only the stream zone was considered, there were significant hotspots ($p < 0.05$) at both the inflow and outflow culverts (Fig 9C). When access to the trough was restricted, the density distribution of sheep locations showed a significant hotspot ($p < 0.05$) in the northwest top corner of the paddock (Fig 9B). The steeper areas of the paddock, adjacent to the stream, had significant cold spots (Fig 9B). When only the stream zone was included in the analysis significant hotspots ($p < 0.05$) were identified at both culverts and near Camera positions 2, 3, 4 and 14 (Fig 9D).

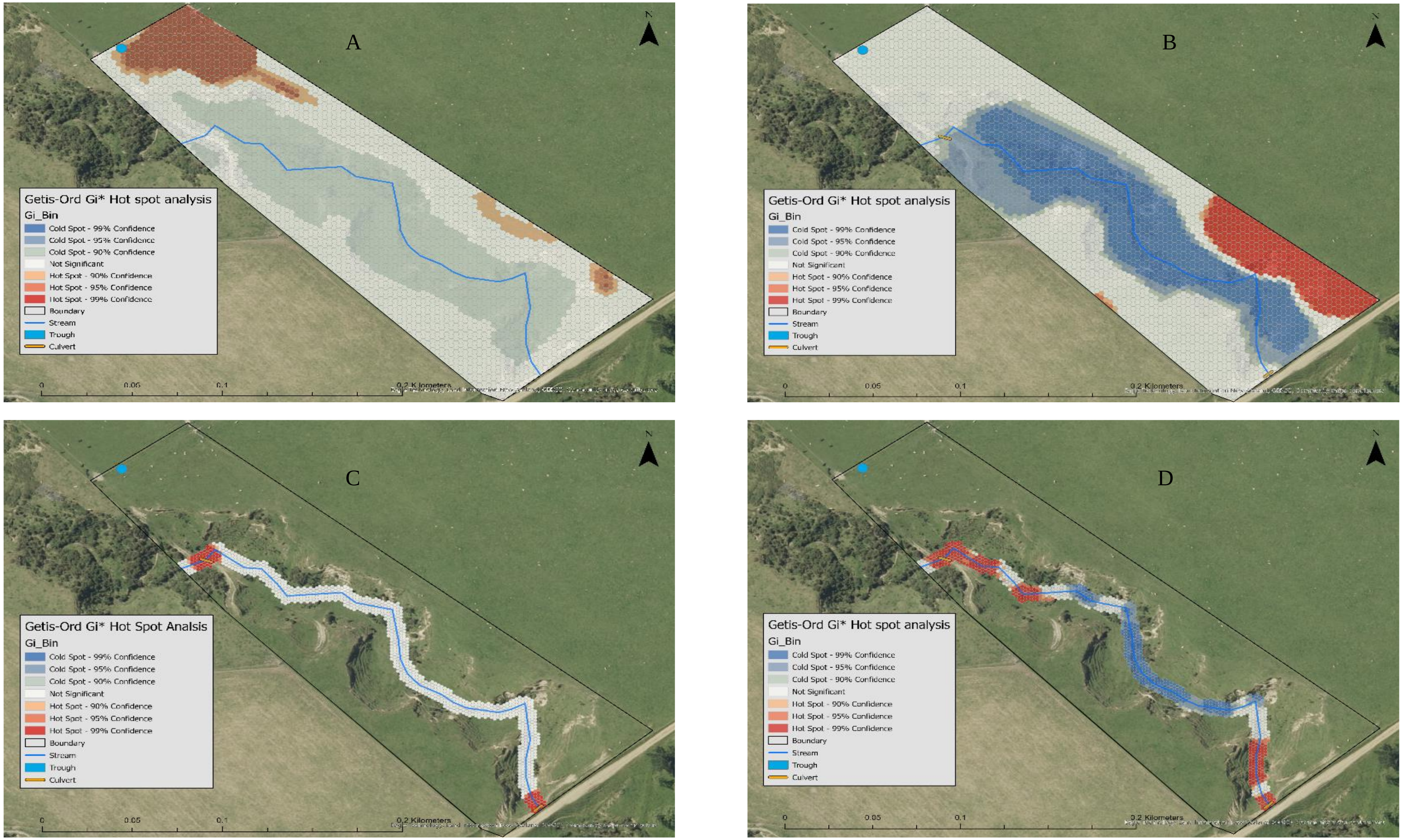

Figure 9 Getis-Ord GI optimized hotspot analysis. A hotspot is an area that has a greater concentration of sheep location clusters compared to the expected number given a random distribution of sheep clusters. Fig 9A shows the entire study site when there was unrestricted access to the trough. Fig 9B shows the entire study site when access was restricted. Fig 9C shows the stream zone (3m either side of the stream) when access to the trough was unrestricted. Fig 9D shows the stream zone when*

2.3.6 Stream flow rate and water quality

The flow rate of water in the stream was higher during the week sheep had unrestricted access to the trough than when access was restricted ($p = 0.0162$). During the unrestricted period flow rate was higher on study D7 than D6 ($p < 0.0001$) but did not differ between D13 and D14 when the water trough was restricted ($p = 0.2278$). Flow rate was higher at the outflow measurement site compared to the inflow measurement site ($p = 0.0034$) (Fig. 10).

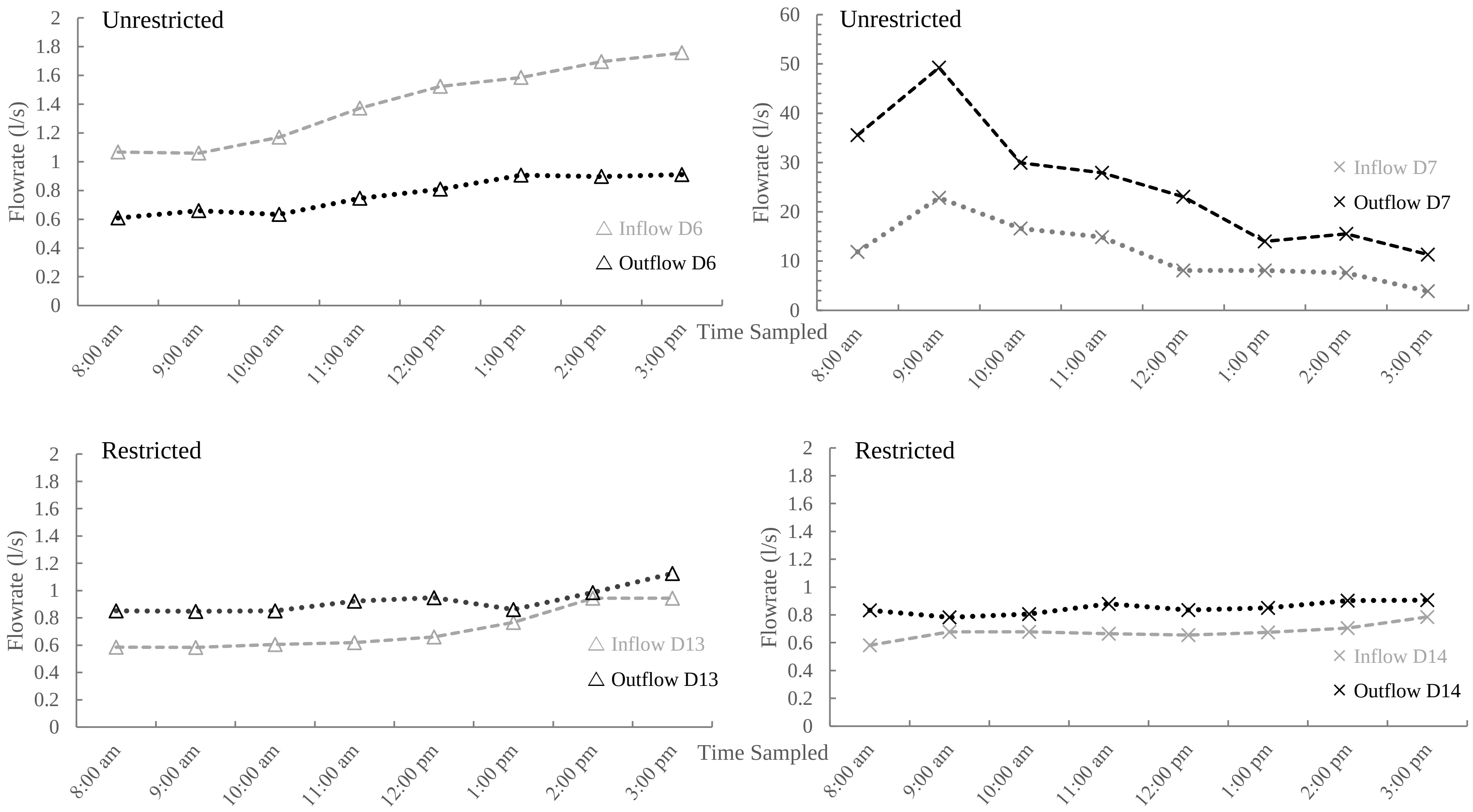

Figure 10 Stream water flow rates (l/s) at each sampling time at the stream inflow (grey line) and outflow (black line) monitoring sites on D6 (△, 15th February 2021) and D7 (×, 16th February 2021) when access to the trough was unrestricted and on D13 (△ , 23rd February 2021) and D14 (×, 24th February 2021) when access to the trough was restricted. Note: Y axis scale is different between treatments and graphs.

Table 7 Mean, median and interquartile range (in parentheses) of the concentrations of suspended sediment (mg/l), total nitrogen (mg/l), total phosphorous (mg/l), ammonium (mg/l) and E. coli (cfu/100 mL) in water samples collected on study days D6, D7, D13 and D14.

	Unrestricted Trough		**Restricted Trough**		**Significance**	
	D6	D7	D13	D14	Treatment	Inflow/ Outflow
Suspended Sediment (mg/l)	4.86, 4.86[b] (3.593,6.499)	22.29, 20.50[a] (11.61,30.61)	6.01, 4.40[b] (3.405, 9.281)	8.36. 1.96[b] (0.742, 5.773)	$p < 0.001$	$p = 0.638$
Total N (mg/l)	0.69, 0.51[b] (0.452,0.690)	2.12, 1.98[a] (1.613,2.74)	0.57, 0.54[b] (0.474,0.707)	0.68, 0.71[a] (0.616,0.767)	$p = 0.01$	$p = 0.01$
Total P (mg/l)	0.02, 0.02[b] (0.014,0.033)	0.12, 0.09[a] (0.09,0.14)	0.03, 0.03[b] (0.023,0.036)	0.05, 0.03[b] (0.019,0.037)	$p = 0.02$	$p < 0.001$
E. Coli (cfu/100ml)	109, 100[b] (94,110)	4906, 4350[a] (3250,6250)	185, 135[b] (100,265)	272, 130[b] (82.5,430)	$p = 0.02$	$p = 0.047$

Ammonium and nitrate-N were below the detection limit in all samples and are not presented. [a,b] Values with different superscripts are significantly different ($p < 0.05$).

2.3.6.1 Suspended Sediment

Suspended sediment concentrations (SSC) and suspended sediment loads (SSL) were higher in the first week compared to the second week ($p < 0.001$, $p = 0.0002$, respectively). In the first week sheep had unrestricted access to the trough and in the second week sheep access to the trough was restricted. During the period that sheep had unrestricted access to the trough SSC and SSL were higher on D7 than D6 ($p <0.0001$, $p <0.0001$, respectively) (Fig. 11). During the period of restricted access to the water trough SSC and SSL did not differ between D13 and D14 ($p = 0.105$, $p = 0.113$). SSC and SSL did not differ between the inflow and outflow water sampling locations ($p = 0.638$, $p = 0.679$, respectively).

2.3.6.2 Nitrogen

Total nitrogen concentrations (TNC) and total nitrogen load (TNL) were higher when sheep had unrestricted compared to restricted access to the trough ($p = 0.0145$, $p = 0.0374$) (Fig. 12). TNL and TNC were significantly higher on D7 than D6 ($p < 0.0001$, $p < 0.001$) (Fig. 12). TNC was higher on D14 than D13 ($p = 0.026$) but TNL did not differ ($p = 0.200$). TNC was higher at the inflow than outflow sampling location ($p = 0.014$) whereas TNL did not differ ($p = 0.638$). Both ammonium and nitrate-N concentrations were below the detection limit of analytical method at all time points (data not shown).

2.3.6.3 Total Phosphorus

Total phosphorus concentrations (TPC) were lower when sheep had unrestricted access to the trough than when restricted ($p = 0.020$). Total phosphorus loads (TPL) tended to differ between treatments ($p = 0.060$) (Fig. 13). When sheep had unrestricted access to the trough TPC and TPL were higher on D7 than D6 ($p < 0.001$, $p < 0.001$, respectively). When access to the trough was restricted TPC and TPL did not differ between D13 and D14 ($p = 0.770$, $p = 0.910$, respectively). TPC and TPL were higher at the inflow sampling location than the outflow ($p < 0.001$, $p = 0.052$, respectively). Total phosphorus load was strongly correlated with suspended sediment load ($R^2 = 0.778$, $p < 0.001$)

2.3.6.4 Escherichia Coli

E. coli concentrations (ECC) and *E. coli* loads (ECL) were higher when sheep had unrestricted access to a trough compared to when they had restricted access ($p = 0.020$, $p = 0.029$, respectively) (Fig. 14). When sheep had access to the trough ECC and ECL were higher on D7 than D6 ($p < 0.001$, $p < 0.001$, respectively). There was no difference in ECC or ECL between D13 and D14 ($p = 0.792$, $p = 0.851$). ECC and ECL were higher at the outflow than inflow sampling sites ($p = 0.047$, $p = 0.009$, respectively). Suspended sediment load and *E. coli* loads were significantly correlated ($R^2 = 0.897$, $p < 0.001$).

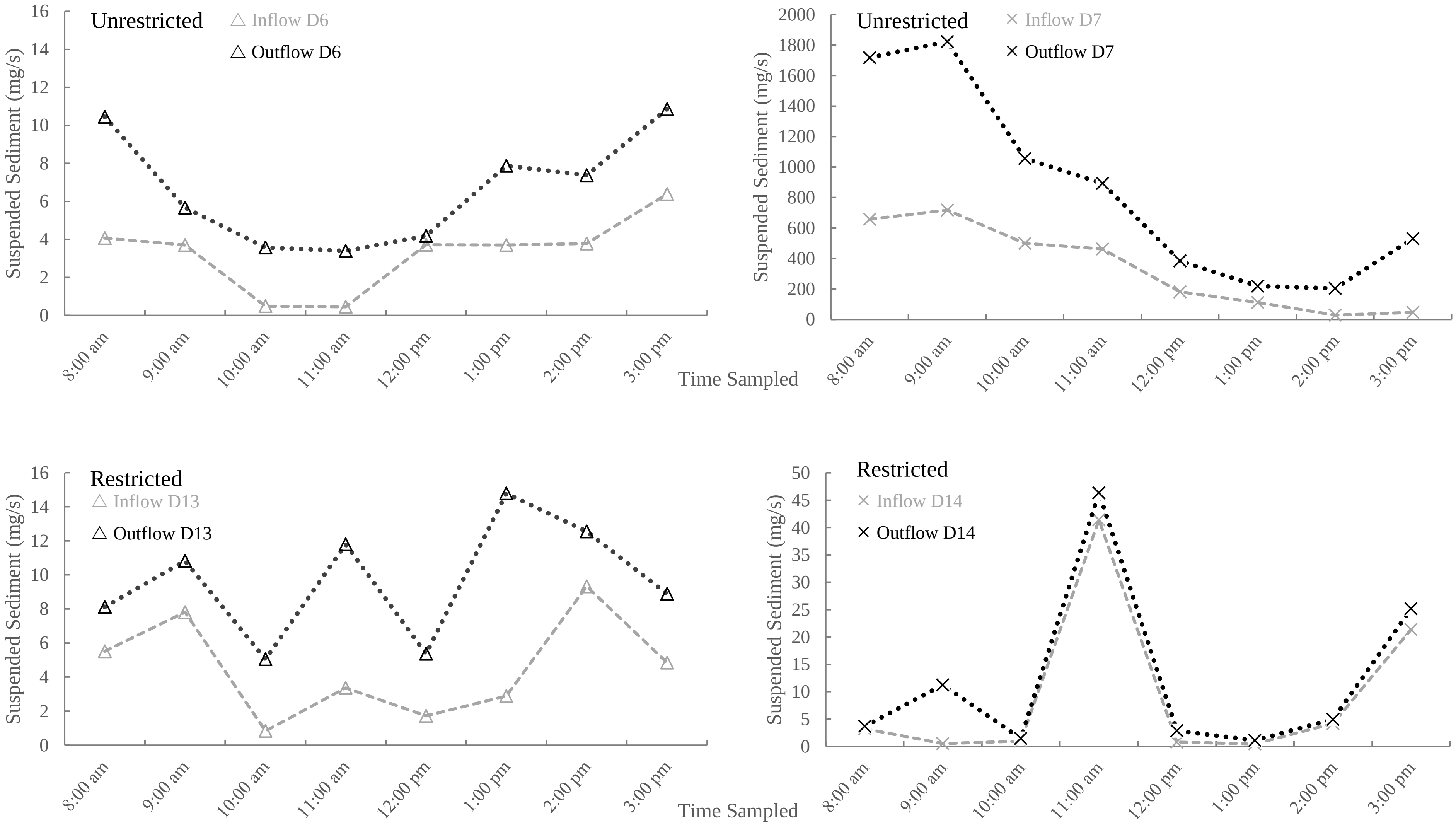

Figure 11 Suspended sediment loads (mg/s) in water samples collected at the inflow (grey line) and outflow (black line) sampling sites on D6 (△, 15th February 2021) and D7 (✕, 16th February 2021) when access to the trough was unrestricted and on D13 (△ , 23rd February 2021) and D14 (✕, 24th February 2021) when access to the trough was restricted. Note: Y axis scale is different between each treatment and graph.

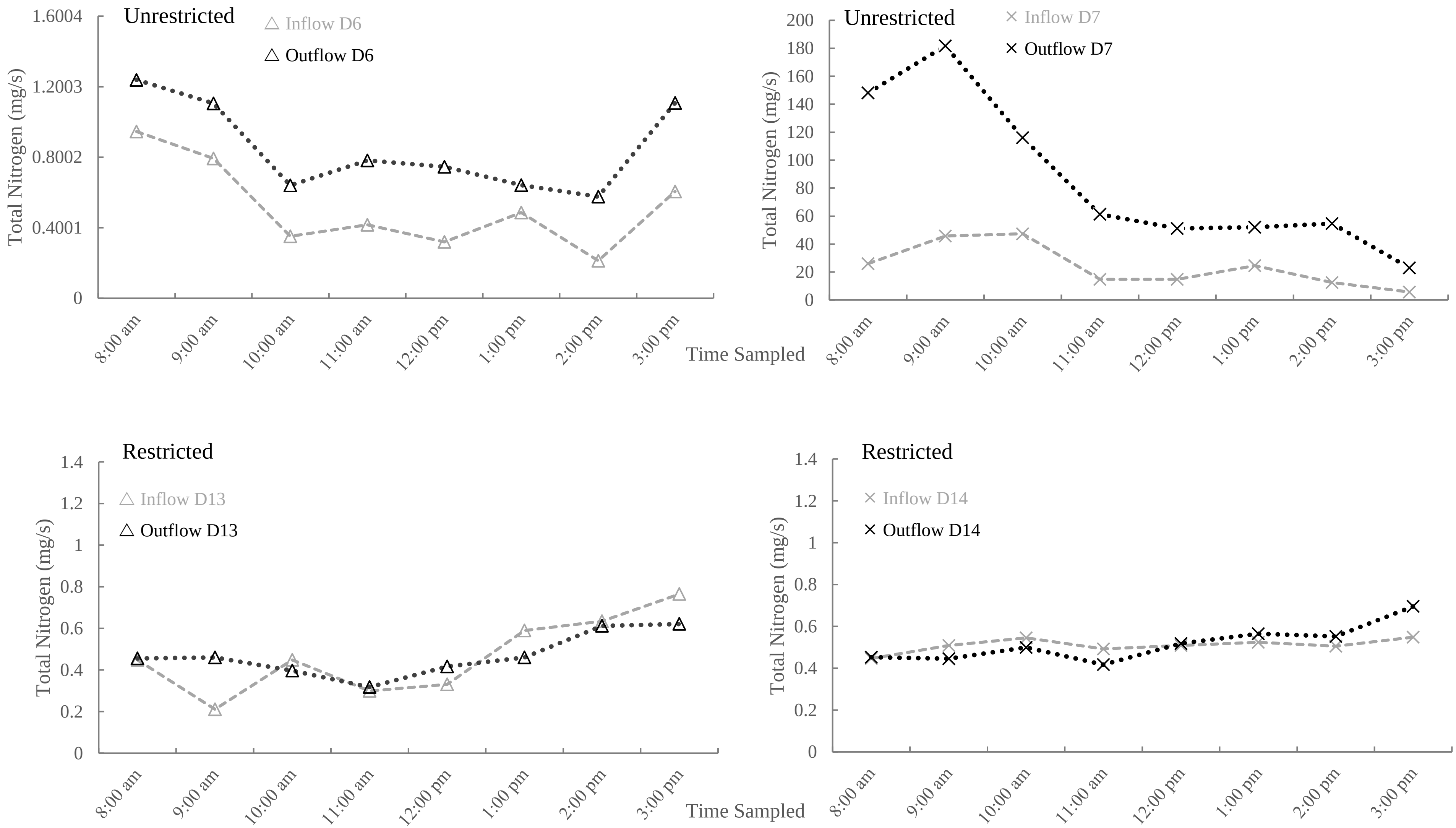

Figure 12 Total nitrogen load (mg/s) in water samples collected at the inflow (grey line) and outflow (black line) sampling sites on D6 (△, 15th February 2021) and D7 (✕, 16th February 2021) when access to the trough was unrestricted and on D13 (△ , 23rd February 2021) and D14 (✕, 24th February 2021) when access to the trough was restricted. Note: Y axis is different between each treatment and each graph.

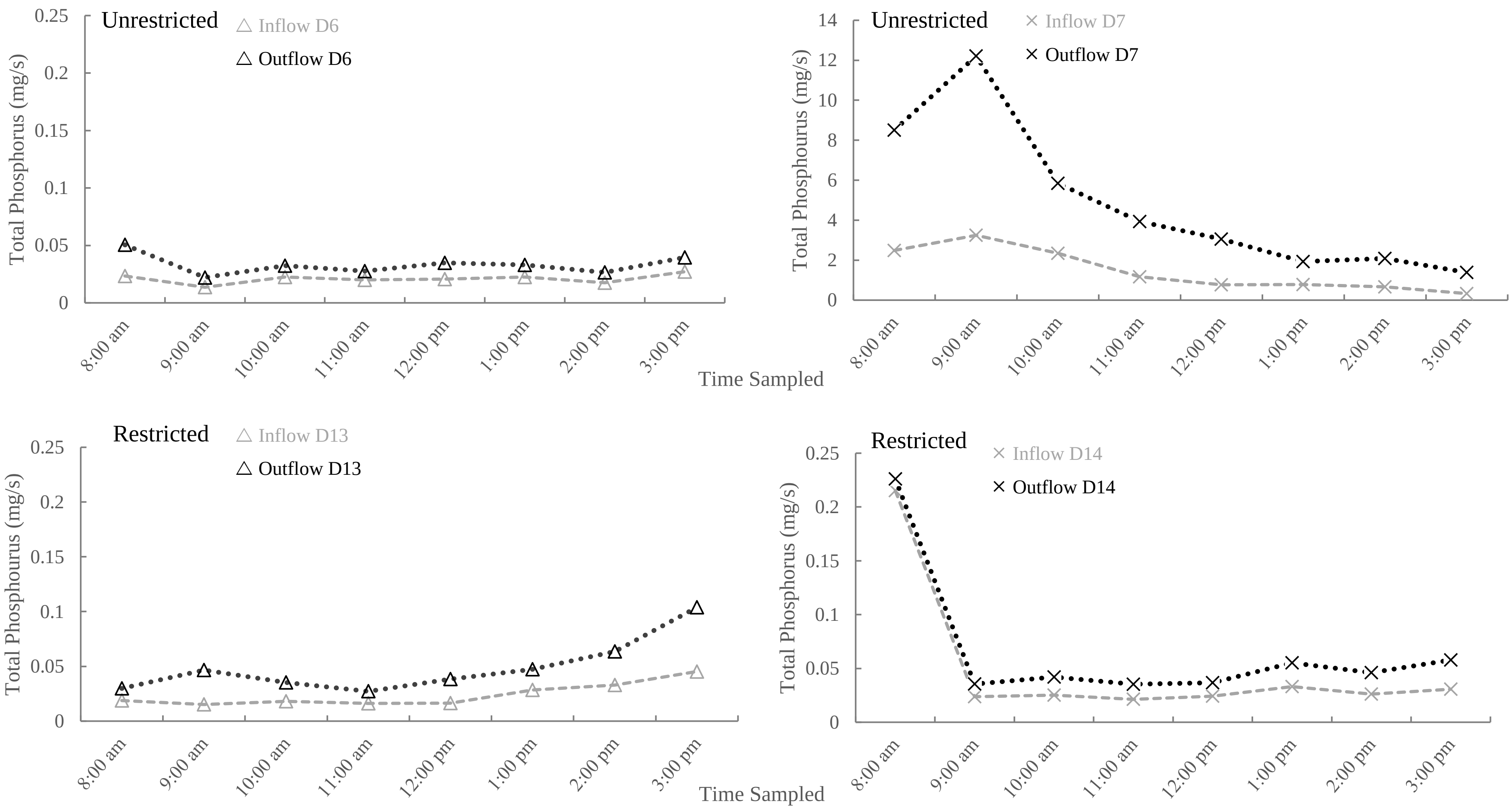

Figure 13 Total Phosphorus loads (mg/s) in water samples collected at the inflow (grey line) and outflow (black line) sampling sites on D6 (△, 15th February 2021) and D7 (✕, 16th February 2021) when access to the trough was unrestricted and on D13 (△ , 23rd February 2021) and D14 (✕, 24th February 2021) when access to the trough was restricted. Note: Y axis scale is different between each treatment and each graph.

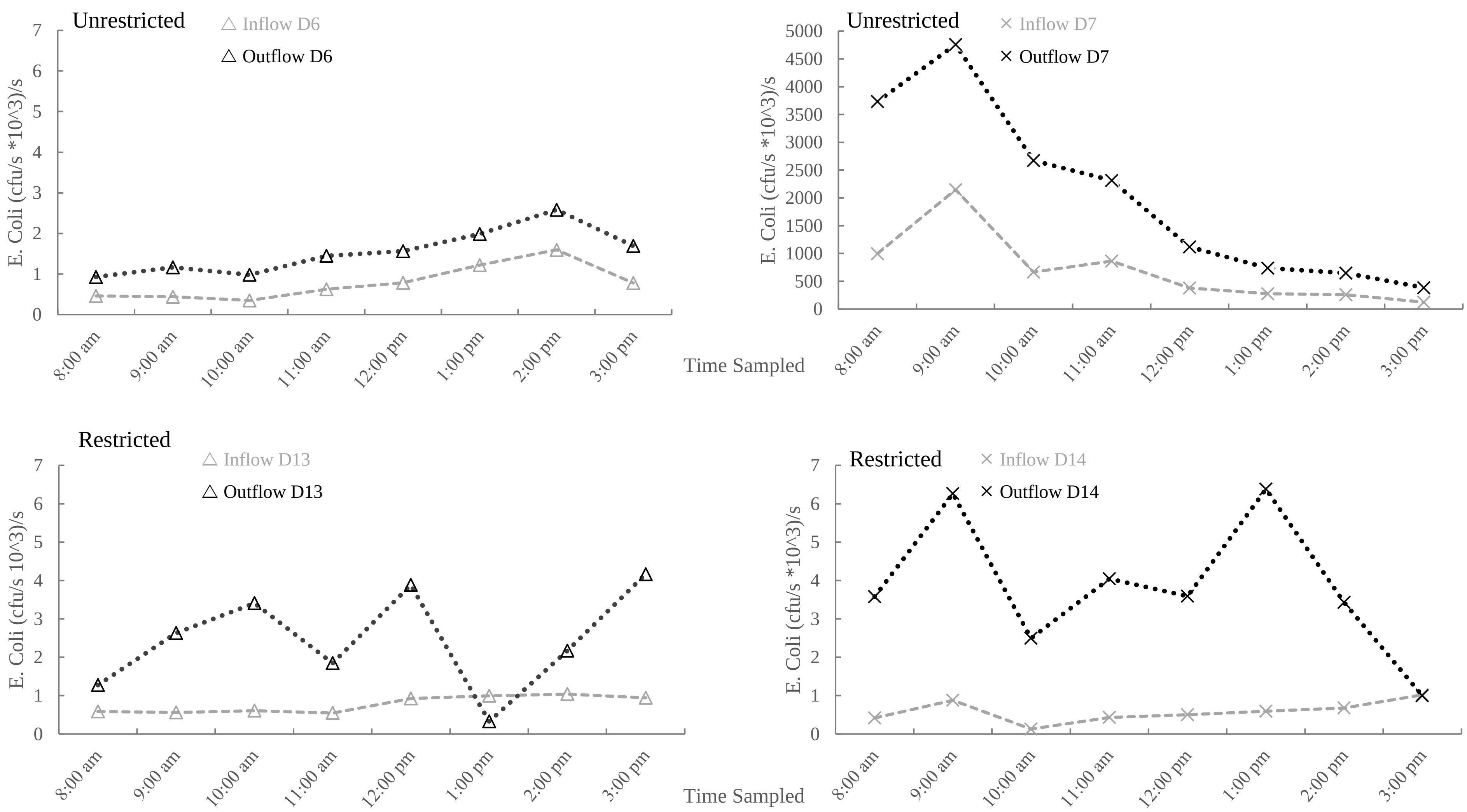

Figure 14 E. Coli loads (cfu/s *10^3/s) in water samples collected at the inflow (grey line) and outflow (black line) sampling sites on D6 (△, 15th February 2021) and D7 (×, 16th February 2021) when access to the trough was unrestricted and on D13 (△ , 23rd February 2021) and D14 (×, 24th February 2021) when access to the trough was restricted. Note: Y axis scale is different between each treatment and each graph.

2.4 Discussion

The aim of the current experiment was to observe the behaviour of sheep around a natural waterway in summer and determine the impact on indicators of water quality. It was hypothesized that when sheep had unrestricted access to a drinking trough, they would not drink from the natural waterway and therefore have no impact on measures of water quality compared to when access to the water trough was restricted. It was predicted that the increased environmental temperatures associated with summer would encourage the sheep to spend more time in and around the free-flowing stream.

During this study, sheep were observed to interact with the stream, although, no sheep were recorded to defecate or urinate within the stream zone. The direct impact of the sheep on the stream and stream bank, therefore, was minimal in terms of direct deposition of nutrients and erosion. In the current study sheep spent more time on the tops of the paddock and frequently used the culverts to cross the stream, rather than walking through the stream. Cameras located in the areas of the stream that had steep slopes on each side (6, 7, 8, 9, 10 and 11), recorded a shorter duration when compared to the cameras with flatter areas (1, 2, 3, 4, 5, 12, 13 and 14) when sheep were in proximity during the restricted trough access period. This may be, in part, due to the slope and ease of access when compared to other areas of the stream that were more accessible. Cameras 2, 3, 5 and 14 had flat areas either side of the stream and were found to have significant hotspots. In addition, these flat areas of the paddock may have had more forage available than the steeper areas.

The greater density of GPS locations on the flat areas of the paddock around cameras 2, 3,5 and 14 may have resulted in greater density of urination and faecal deposits. Betteridge et al. (2017) showed that among beef cattle, flatter areas of a paddock had more urination events than steeper areas. Saggar et al. (1990) also observed that there was elevated excreta deposition on flatter areas of a paddock as opposed to a stream where animals tended to spend more time. Similarly, Guevara-Escobar et al. (2007) observed that sheep and cattle preferentially grazed more open areas, but tended to camp under trees and sheltered areas. This suggests that if the slope surrounding a stream was not as steep as in the current study, or if the paddock that contained a stream was surrounded by flat areas, sheep may interact more readily with the stream. Furthermore, this suggests that slope influences the amount of effluent deposited by sheep and this could potentially lead to negative consequences on water quality relative to stock duration in a location.

The availability of the water trough had no effect on the frequency of drinking or walking in the stream. Despite this, when access to the trough was restricted, sheep were observed to congregate in areas around camera positions 2, 3, 5 and 14 which were identified in the hotspot analysis (Fig. 10D).

Although sheep that do not have access to a water source must obtain their daily water requirement from the feed they consume (Lynch et al., 1972), previous research suggests that sheep can satisfy their water requirements through food intake and dew alone (Putfarken et al., 2008). In the current study the moisture content of pasture ranged from 53.5% in samples collected beside the stream to 71.7% on the flat areas at the top of the paddock (Table 4). Based on the moisture content the pastures in the study site appeared to have been sufficient to meet water requirements of the ewes in the study. The herbage mass of perennial ryegrass swards can influence both the voluntary dry matter intake by the sheep and the sward characteristics (Garry et al., 2021). Pasture production on sloped areas of paddocks may be reduced due to the effect of shading (Guevara-Escobar et al., 2007) due to intercepted light creating shaded areas.

The creation of the hotspot areas did not appear to result in elevated concentrations or loads of total nitrogen, total phosphorus, nitrate, ammonium or suspended sediment in stream water. The concentrations of nitrate and ammonium, total nitrogen, and total phosphorus were low for this time of year (Wilcock et al., 1999) and only increased in response to a rain event on D7. During summer nitrate N found in streams draining from agricultural catchments can be virtually near zero and TN mostly comprises of organic nitrogen whereas concentrations of total phosphorus (TP) vary in accordance with farm fertiliser application rates (Wilcock et al., 1999).

Rainfall occurred during the water monitoring on D7 with a total of 24.5mm of rain was recorded resulting in an increase water flow rate of the stream. As a consequence, concentrations of *E. coli*, TN, TP, and SS measured in the water samples at both the inflow and outflow sampling locations were elevated relative to samples collected on D6. In the current study there was a strong correlation between concentrations of suspended sediment and both *E. coli* and TP loads. Over summer lower rainfall results in the build-up of nutrients in the surface soil profile and dung is left undisturbed. Rainfall events, therefore, generate surface runoff which can mobilise sediment, nutrient and pathogen loss into streams. Cournane et al. (2011) reported that rainfall events complimented by soils experiencing periods of hydrophobicity as a result of dry spells (i.e. in summer) exacerbated the mobilisation of nutrient, sediment and pathogen loss which they attributed to soil infiltration-excess conditions. Although a summer rainfall event may not contribute a lot of water relative to winter rainfall events, the combination of the soil condition and pasture cover may create circumstances favourable for considerable nutrient and pathogen loads entering a stream.

In the current study the median *E. coli* concentration recorded on D7 during the rainfall event was 4350 cfu/100ml. This value exceeds the freshwater recreation microbial assessment category water quality guideline D grade threshold of >550 MPN/100ml which is roughly equivalent to colony forming units (Jenkins et al., 2009). Collins et al. (2005) reported a greater range in values of peak *E. Coli* concentrations that ranged from 5 x 10^3 to 7 x10^6 MPN/100ml following a substantial storm event. The differences in *E. coli* concentrations in the current study, and that of Collins et al. (2005), could be explained by differences in catchment area, stock type and stocking rate and duration and intensity of the rainfall. Subsurface drainage systems primarily result in the pathogen loading of streams but peak load occurrences will likely occur during events that produce overland flow (Dorner et al., 2006). The availability and location of water and shade, landscape topographical features (e.g., hillslopes), and pasture growth and season, contribute to the concentration of animal excreta within the landscape (Aarons & Gourley, 2013). Excretal deposits tend to lead to higher concentrations of nutrients in the surface soil horizon and are significant sources of readily available sediment, N and P, and pathogens (Bilotta et al., 2007). These deposits, therefore, pose a high risk to surface water quality if they coincide with surface runoff flow paths and the potential for these to enter a waterway increases as a result of rainfall. The *E. Coli* loads recorded during the rain event on D7 had the potential to cause significant adverse implications to other water users of the stream. Management practices that result in less faecal deposits being left on a paddock such as decreasing the rotation length or stocking density will likely minimise the risk of faecal contamination of streams.

The increase in TN that entered the stream on D7 in the current study was likely to be due to a combination of labile N within the soil that was mobilised during rainfall and recent sheep dung and urine deposits. The TN concentrations were low on all sampling days (<1.3mg/L^{-1}) except on D7 when the rainfall event occurred. The threshold of tolerable concentrations is 2.38 mg L^{-1} dissolved inorganic nitrogen recommended by the Australian and New Zealand Guidelines for Marine and Freshwater quality (Australian Government 2021). The concentration of N in fresh sheep urine ranges from 3.0 to 13.7 g N/L $^{-1}$ (Bristow et al., 1992). Although deposition of urine or dung directly into the stream was not observed in the current study, it would be useful to measure if a single urination event could generate a detectable change in stream N concentration. These results suggest in the current study sheep did not influence the total nitrogen loads within the stream directly, rather that rainfall mobilised historic nitrogen within the paddock to the stream.

The TPL was higher at the inflow water sampling location compared to the outflow and was higher following the rainfall on D7 compared to D6. Total P load was strongly correlated with suspended sediment load. In hill country soils, where soil erosion tends to be elevated, particulate loss of P is the dominant form of P loss by overland flow (Hart et al., 2004). Typical nutrient application rates in sheep dung patches are 130 kg N/ha and 35 kg P/ha (Williams & Haynes, 1995) and sheep excreta that was present in the paddock would have contributed to an increased concentration of P in the stream due to surface runoff (Hooda et al., 2000). Suspended sediment load was higher on D7 compared to D6 and was probably linked to the rainfall occurring on that day. Suspended sediment load also peaked when the water trough was restricted at 11am over both sampling days. This could be in part due to the increased sheep activity during the middle of the day compared with later periods of the day or may reflect processes occurring further up the stream catchment area.

2.5 Conclusion

During summer, the behaviour of sheep around the stream was not influenced by the availability of a drinking trough. When sheep had no access to the trough, however, they spent more time within areas of the stream that were easier to access and were observed to drink from the stream. There were no recorded instances were sheep defecated into the stream and two occurrences of urination. This study suggests that there was a negligible influence of sheep on water quality and any effects were likely due to a rainfall event.

Chapter 3 The interaction of ewes with a natural waterway in Autumn and the impacts on water quality.

3.1 Abstract

Agricultural stock access to waterways has been shown to increase the risk of sediment, nutrient and pathogen loss and is therefore a concern for water quality. The activity of sheep around waterways and their impact on water quality, however, has not been studied in New Zealand. Information on the potential impacts of sheep on waterways is critical to inform policy development and future regulation. The current study was conducted in April (Autumn) on a hill country farm near Palmerston North, New Zealand. The behaviour of mixed age ewes (n=40) was monitored using accelerometers (n=40) and global positioning system (GPS) units (n=20) as they grazed a 2.94ha paddock that was transected by a stream (<1m wide). The study examined the behaviour of sheep during a period of unrestricted access to a reticulated water trough or followed by a period of restricted access. Water quality and flow rate was intensively monitored for two eight-hour periods during each trough treatment period and analysed for nitrogen, phosphorus, sediment and *Escherichia coli* (*E. coli)*. Minimal interaction of sheep with the stream zone (area within 3m either side of the stream) was observed and the amount of interaction did not differ when access to a drinking trough was restricted or unrestricted (1.74 vs 1.10% of all GPS location points recorded, respectively). There appeared to be an individual sheep preference for entering the stream zone with six ewes contributed 40% of the total video footage captured at each of the camera locations and the remaining 34 sheep contributing the remaining 60%. One sheep was not observed to enter the stream zone at any time during the study period. This suggests that interaction of sheep with waterways may be a learned behaviour and as such there may be an opportunity to influence sheep behaviour by dissuading them from interacting with streams. The topography of the paddock influenced sheep behaviour with more time ($p < 0.05$) spent on flatter areas of the paddock relative to the steeper regions (> 25°). Sheep spent more time in the stream zone when access to the trough was restricted ($P<0.05$). The predominant behaviour of sheep in the stream zone was grazing. Water samples showed that nitrate-N concentrations were below the detectable limit of the analysis method throughout the study period and ammonium concentrations were only detectable following rainfall events on D9 and D10. Water sediment concentrations were higher when sheep had restricted access to the drinking trough compared unrestricted access ($P<0.05$). Water *E. Coli* concentrations were detected at higher concentrations at the outflow than the inflow water sample collection site, suggesting that the presence sheep in the paddock were the source of the additional bacteria. Together

these results suggest that the influence of sheep on water sediment and *E. coli* concentrations was likely due to their presence in the paddock rather than directly depositing urine and faeces into the stream. Few sheep spent time in stream zone during autumn and had a minimal impact on water quality.

3.2 Introduction

The Resource Management Act in New Zealand was amended in 2020 to regulate stock access to wetlands, lakes, rivers and streams (>1 m wide) by cattle, deer and pigs (Ministry for the Enviornment, 2020). Specific requirements vary depending on the stock class, water body type and slope, but currently do not apply to sheep. In 2019 the New Zealand sheep population was 26.8 million (Statistics, 2021) and traditionally New Zealand has been the world's largest exporter of lamb contributing more than 40% of total global exports (Ledgard et al., 2011). In 2010, Bensemann and Shadbolt (2015) reported that exports of sheep meat contributed NZD $2.7 billion to the New Zealand economy representing 6.3% of all merchandise exports.

In New Zealand, hill country environments account for 30% of the total land area and 71% of pastoral land use in (McCoard, 2017). Despite the importance of the sheep industry to New Zealand and to export partners, there has been no research sheep movement around natural waterways and the potential impacts on water quality on New Zealand hill country farms. This information is critical to determine if sheep should be included in current stock exclusion regulations.

In the Manawatu region of New Zealand autumn is typically characterised by slight increases in monthly rainfall, fewer sunshine hours, lower temperatures, and the occasional frost compared to summer. The precipitation pattern over the past three decades show that there has been an increase in the prevalence of drier summers and autumns in the North Island of New Zealand when compared with long term annual weather metrics (Silungwe et al., 2010). A change in the frequency and intensity of precipitation events causes variation in annual and seasonal precipitation (Caloiero, 2015) with heavy nutrient loading of water bodies during periods of increased precipitation (Zimmer & McGlynn, 2017). The Manawatu has relatively high seasonal (monthly) variation in dissolved nutrient (Nitrate-N and dissolved reactive phosphorus (DRP)) and total nitrogen concentrations in river water (Elwan et al., 2018). Concentrations are higher in winter (June to August) and spring (September to November) than in summer (December to February) and autumn (March to May). Baseflow in stream or rivers is supplied by subsurface drainage and/or groundwater contributions and this flow pathway transports dissolved nutrients (nitrate-N and DRP) through the soil profile to surface water.

The seasonal grazing movement of sheep is influenced by the growing seasons of forage and the weather (Dwyer, 2008). Some hill country slopes have higher levels of evapotranspiration than others due to variations in solar radiation and the location of the sun relative to the slope as a result of their aspect (Aguilar et al., 2010). This variation in evapotranspiration can cause plant growth to vary spatially across the hill slope and can therefore generate an uneven distribution of excreta due to sheep grazing preference. Areas with greater excreta deposition are prone to nutrient loss when rain events occur, or the water table rises.

The objective of this study was to determine the differences in sheep behaviour and spatial distribution of sheep in a hill country environment transected by a natural stream. Further, this study aimed to determine any impacts of sheep on stream water quality in autumn when access to a water trough was unrestricted and restricted. It was hypothesised that free access to a water trough would result in sheep showing fewer interactions with the natural stream and a reduced impact on water quality. In addition, that increased precipitation in autumn would result in higher background stream nutrient loads entering the study area, compared to summer.

3.3 Methods

For a detailed description of the study design, sheep behaviour analysis, water characteristic sampling process and pasture collection methods please refer to Chapter 2.2.

All the procedures in this study were carried out with the approval of the Massey University Animal Ethics Committee (MUAEC 19/62). The study was conducted at Massey University's hill country farm, Tuapaka, located approximately 15 km north-east of Palmerston North (40.3346° S, 175.7316° E) from the 7th to 20th of April 2021 (D1 to 14). The study used the same mixed-age ewes that had been enrolled in the summer study (n=40) and the same 2.94 ha study paddock. The study paddock contained a discrete sixth order natural stream as classified by the Strahler (Hughes et al., 2011). Sheep were continuously stocked on a perennial ryegrass pasture maintained above 1000 kg DM/ha. Pasture sampling to determine moisture was conducted on D1, D6, D8 and D14. The study used a crossover design whereby sheep had unrestricted access to a water trough for the first week of the study (week 1) followed by a period of restricted access when the trough was covered (week 2).

Each sheep was fitted with a numbered collar to which an accelerometer was attached. Accelerometers were programmed the night prior to the start of the study. Each sheep was identified with their accelerometer number spray painted onto their flank using stock spray (Sprayline, Donaghys, Christchurch, New Zealand). Accelerometer data was downloaded through Actilife® and proximity data was visualised through IBM SPSS Statistics 27 (Armonk, New York, United States of America). In addition to the accelerometers twenty sheep were randomly allocated a global positioning system (GPS) unit fixed to a neck collar for two days of each study week (week 1: D1-3 and week 2: D7-10).

Video surveillance cameras (numbered 1 to 14) were attached to metal stakes and placed at intervals of between 5 to 15 m along the entire length of the waterway with an additional camera (camera 15) placed near the single water trough in the paddock (n=1; Chapter 2, Fig 1). Behavioural footage was coded using the behaviour software BORIS (Friard & Gamba, 2016).

Water samples were collected simultaneously every hour from both the inflow and outflow sections of the stream between 08:30 and 13:30 on days D6, D7, D13 and D14 (12^{th},13^{th}, 19^{th} and 20^{th} April). Nitrate and ammonium samples were analysed using a visible dye red azo and phenol Prussian blue colourmetric analysis for nitrate-N and ammonium respectively and analysed using an auto analyser (Pulse Instrumentation Ltd, Saskatoon, Canada). Nitrate-N concentrations were below the detectable limit of the analytical method throughout the study period.

Total nitrogen samples were digested with persulphate (Hosomi & Sudo, 1986) and then analysed with an auto analyser (Pulse Instrumentation Ltd, Saskatoon, Canada). Dissolved reactive P samples were analysed using molybdenum blue colourimetry and DRP concentration measured via flow injection analysis (APHA 4500-P G (modified) 23rd ed. 2017). Total P samples underwent acid persulphate digestion and P concentration was determined using automated ascorbic acid colorimetry via Flow Injection Analysis (APHA 4500-P H (modified) 23rd ed. 2017). Dissolved reactive P samples were contaminated and could not be processed. Suspended sediment was determined by filtering a known volume of sample (~1 l) through a pre-weighed Whatman 110mm glass microfibre filter (CAT No.1822-110, Little Chalfont, United Kingdom) to less than 1.2µm.

3.3.1 Statistical analysis

Behavioural data was analysed using the statistical software SAS. The total number of behaviour events and the total duration were tested for normality (students t test) and were compared between treatments and camera locations using the nonparametric, univariate analysis (Kruskal-Wallace). Coordinates created from the GPS units were analysed using GIS ArcPro (Esri, 2021). The plots were clipped to the paddock boundary so that no GPS coordinates were included that were not consistent with the study site. Hotspot geoprocessing programmes were used to create visual representations of sheep spatial location and movement within the study site. Accelerometer data was downloaded through Actilife® and proximity data was visualised through IBM SPSS Statistics 27 (Armonk, New York, United States of America).

Water sample data was analysed using the statistical software SAS. To allow the analysis of data where < 20% of values for an individual parameter were below the analytical method detection limit data were replaced by the detection limit divided by the square root of two (Sanford et al., 1993). For variables with >20% below the detection limit statistical analyses were not conducted. Nonparametric, univariate analysis (Kruskal-Wallace) was used to determine significant difference between treatments (unrestricted access, restricted access), between samplings days within the treatments and between the stream inflow and outflow measures.

3.4 Results

3.4.1 Weather

During the autumn experiment, there was a total of rainfall of 24.8mm. The maximum daily temperature gradually declined over the duration of the experiment. The minimum temperature ranged between 3.7 and 14.6°C and the maximum temperatures between 16.4 and 24.6°C.

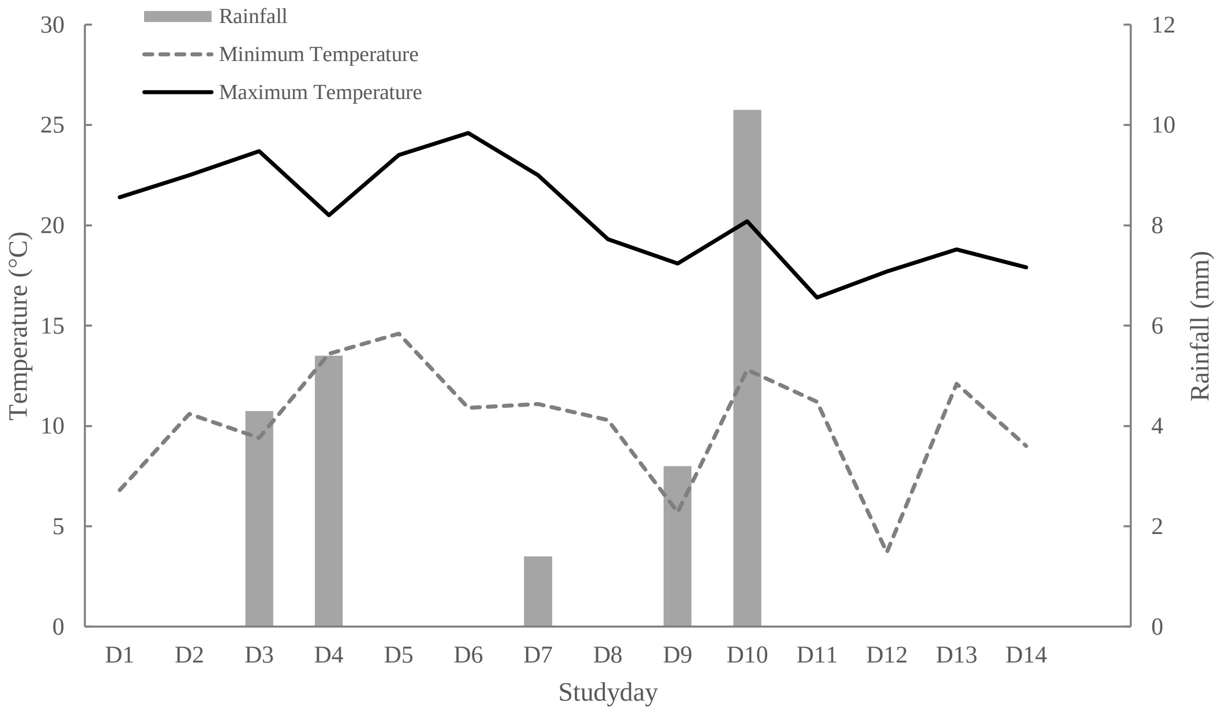

Figure 15 Daily rainfall (mm) and temperature (°C) range during the autumn study period (7th-20th April 2021). Water sampling was carried out on D6 and D7 (unrestricted trough access) and D13 and D14 (restricted trough access), annotated above.

3.4.2 Pasture Analysis

Pasture masses and moisture content did not differ between collection days ($p = 0.189$ and 0.192, respectively) or sampling positions ($p = 0.564$ and 0.668, respectively).

Table 8 Pasture mass (kg DM/ha) and moisture content (%) during the autumn trial period. Top is the northern flat area of the paddock; bottom is the western flat area. Pasture moisture content was taken from three random locations across the gradient of the slope, top being at the top of the paddock, middle being the sloped area of the gully and bottom being areas adjacent to the stream and at the bottom of the gully.

Study day	**Date**	**Sampling position**	**Mean**
		Pasture Mass (kg/DM/ha)	
D1	7/4/21	Top	2284.02
D1	7/4/21	Bottom	2165.52
D6	12/4/21	Top	1963.28
D6	12/4/21	Bottom	1988.56
D8	14/4/21	Top	1715.22
D8	14/4/21	Bottom	2013.84
D14	20/2/21	Top	1955.38
D14	20/2/21	Bottom	1833.72
		Moisture content (%)	
D1	7/04/2021	Top	90.72
D1	7/04/2021	Middle	64.71
D1	7/04/2021	Bottom	79.62
D6	12/04/2021	Top	79.20
D6	12/04/2021	Middle	80.15
D6	12/04/2021	Bottom	84.29
D8	14/04/2021	Top	85.70
D8	14/04/2021	Middle	87.51
D8	14/04/2021	Bottom	89.10
D14	20/04/2021	Top	73.05
D14	20/04/2021	Middle	73.36
D14	20/04/2021	Bottom	79.80

3.4.3 Sheep Behaviour

During the Autumn experiment, one sheep contributed 10% of the total observed behaviours. Combined the six sheep with the most behaviour observations contributed 40% of the total recorded behaviours observed within the stream zone. Of the remaining 34 sheep, 15 contributed between 2-3.5% each accounting for 39% of the total recorded behaviours. The remaining 17 sheep contributed less than 2% each with a combine contribution of 21% of the observations. There were no recorded instances of sheep being observed to urinate or defecate in the stream zone.

Grazing was the dominant behaviour exhibited by sheep within the riparian zone (607 of 911 observations; (Table 9). Cameras 7, 9 and 12 recorded the longest median grazing bout duration (64, 67.1, 63.6s respectively) and Camera 3 had the lowest (4.8s). There were 220 walking bouts observed which were generally less than 10s long. The frequency of walking events differed between Camera locations ($p = 0.002$) with Camera 1 which was situated near the culvert recording the highest number of walking observations ($n = 67$), whereas Cameras 5 and 10 which were located in steeper areas of the gully, recording a lower frequency ($n = 2,3$ respectively).

Table 9 The number of sheep (n) and the median and interquartile range in parentheses of the duration in seconds (s) sheep were observed to show each behaviour (walk, graze, be stationary, lay down and other) at each camera location. – indicates that no sheep were observed to show the behaviour in video footage recorded at the camera location.

Camera	Sheep behaviour duration (s)									
	n	Walk ѽ	n	Graze ↄ	n	Stationary Д	n	Lying ф	n	Other ǯ
1	67	6.7 (4.2-11.8)	75	15.1 (11.4-29.5)	12	10.6 (3.4-14.2)	-	-	2	3.8 (2.6-5.0)
2	15	8.2 (6.4-15.6)	54	15.8 (14.3-44)	5	7 (5.16-15.4)	5	61 (59.9-60.9)	-	-
3	13	1.4 (0.8-2.5)	61	4.8 (3.1-12.23)	7	2.4 (0.8-2.8)	-	-	-	-
4	32	6.2 (3.8-9.9)	74	38.3 (24-68.3)	8	11.3 (5.8-14.5)	-	-	1	6.4 (6.4-6.4)
5	2	1.6 (1.1-2.1)	30	32.6 (27-58.2)	4	14 (4.4-23.2)	-	-	-	-
6	8	3.9 (3.2-10.3)	29	37.8 (16-59.9)	4	8.7 (5.6-13.3)	-	-	-	-
7	15	2.4 (1.9-8.4)	50	64 (31.8-120)	12	3.9 (3.1-9.2)	-	-	-	-
8	13	11.3 (4.4-22.7)	33	31.1 (26.8-57.4)	3	4.5 (4.2-5.3)	-	-	1	3.4 (3.3-3.4)
9	14	11.6 (3.3-20.7)	75	67.1 (29.5-162)	7	4.7 (3.6-12.1)	-	-	-	-
10	3	2.1 (1.6-2.3)	16	44.8 (30.3-68.9)	1	6.8 (6.8-6.8)	-	-	-	-
11	11	13 (1.9-33.3)	7	10 (3.7-39.1)	5	44.6 (24.6-46)	-	-	-	-
12	14	9 (5.5-11.3)	35	63.6 (32.3-102)	6	8.4 (3.9-8.5)	-	-	-	-
13	13	6.6 (2.4-12.8)	58	57.1 (31.7-129)	1	53.8 (53.8-53.8)	-	-	-	-
14	-	-	10	24.7 (14.4-31.2)	-	-	-	-	-	-

– indicates that no sheep were observed to show the behaviour in video footage recorded at the camera location, ȣ = sheep moved from one point to another, ↄ = sheep harvested vegetation from the ground, Д = sheep was inactive either standing or sitting, ф = sheep was lying down, ǯ = any other behaviour not defined in the ethogram.

During the entire study period there were eight instances in which sheep were observed to drink from the stream (Table 10). Two sheep were observed to drink from the stream on more than one occasion and the remaining six drank once. The number, and duration, of drinking events was not affected by access to the trough ($p = 1.00$ and $p = 0.387$, respectively). Camera location did not influence the frequency ($p = 0.670$) or duration sheep were observed to drink ($p = 0.283$; Table 10). Sheep were recorded sniffing the stream water on 12 occasions, however, sniffing behaviour was not influenced by trough treatment ($p = 1.00$). Sniffing behaviour was of a short duration (<5.5 seconds) and usually preceded another behaviour such as walking in the stream or commencing grazing in the riparian zone.

The video cameras along the stream recorded 214 occasions when sheep interacted with the stream (Table 10) which was defined as a behaviour performed within 1 metre of flowing water. The total number of stream interactions at each video camera location (p = 0.161) and the duration of behaviours did not differ between the two trough treatment periods (p = 0.103). Cameras 7, 9 and 13 recorded the highest number of stream interaction events (n = 32, 31 and 47, respectively) with the highest median duration (40.2, 43.7 and 37.0s respectively).

Sheep were observed to walk in the stream on 170 occasions (Table 10). There were three sheep that were not observed to walk in the stream at any time during the study period. Five sheep walked in the stream on one occasion, 20 between two and five occasions and seven sheep on more than ten occasions. One sheep was recorded to walk in the stream on 23 occasions. The frequency and duration of walking in the stream did not differ between the two trough treatment periods (p = 0.795 and p = 0.480, respectively).

***Table 10 The number of sheep (n) and the median and interquartile range in parentheses of the duration (s) each water related behaviour was observed (drink, sniff, interact with stream and walk in stream) at each camera location. – indicates that no sheep were observed to show the behaviour in video footage recorded at the camera location*.**

Camera	**Sheep behaviour duration (s)**							
	n	**Drink water ϕ**	**n**	**Sniff water ¥**	**n**	**Stream Interaction §**	**n**	**Walk in stream Ӂ**
1	-	-	1	5.2 (5.2-5.2)	10	15.6 (14-22.9)	-	-
2	-	-	-	-	1	1.9 (1.9-1.9)	-	-
3	-	-	-	-	17	4.4 (2.4-9.0)	13	4.4 (3.1-5.7)
4	-	-	-	-	26	16.7 (10.4-43.4)	13	15.7 (13.9-28.5)
5	3	22.3 (13.2-33.6)	3	2.4 (2.29-3.9)	8	22.3 (12.4-35.2)	17	29.4 (22.8-36.9)
6	2	9.5 (3.62-15.4)	2	5.1 (2.6-7.5)	10	16.6 (8.5-31.4)	22	28.1 (15.3-45.9)
7	-	-	-	-	32	40.2 (21.2-69.4)	26	33.8 (12.5-77.3)
8	2	24.5 (22-26.9)	1	3.6 (3.6-3.6)	13	24.3 (9.6-30.6)	11	16.5 (3.8-46.8)
9	-	-	3	2.3 (2.0-3.1)	31	43.7 (27.7-93.5)	45	55.8 (18-122)
10	-	-	-	-	7	31.7 (26.0-64.8)	4	47.4 (16.2-71.2)
11	-	-	-	-	4	24.3 (4.7-41.0)	-	-
12	-	-	2	2.0 (1.0-2.9)	16	32.9 (24.9-70.4)	4	29.5 (15.4-34.7)
13	1	5.2 (5.17-5.17)	-	-	39	37 (27.9-90.7)	12	32.1 (17.4-78.7)
14	-	-	-	-	-	-	3	31.3 (9.0-31.2)

- no sheep were observed to show the behaviour at the camera location, ϕ = sheep drank from the stream, ¥ = sheep had muzzle orientated toward water and inhaled, § = sheep was within 1m of the stream and engaged in other behaviours, Ӂ = sheep was in the stream, moving or stationary without drinking.

3.4.4 Actigraph Proximity

The duration that sheep were recorded to be within 3m of the camera locations differed between trough access periods ($p<0.001$; Fig. 17). When sheep had access to the water trough, they spent longer within 3m of the cameras along the stream than when access was restricted ($p < 0.05$; Fig. 16).

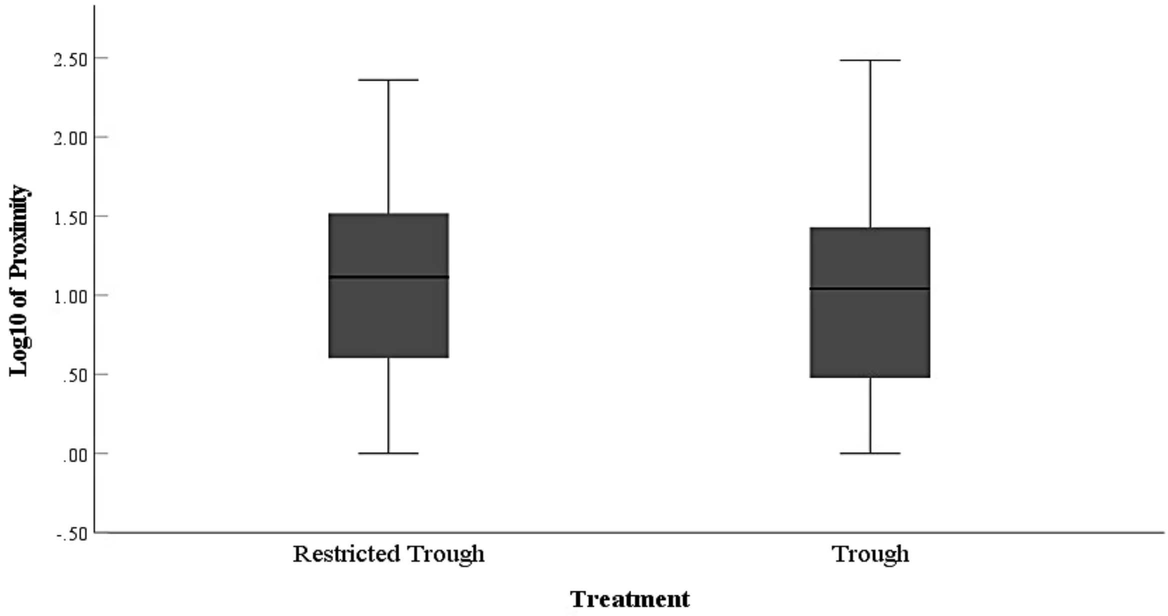

Figure 16 Boxplot of log10 transformed duration (sheep minutes) sheep were estimated to be within 3m of camera locations during the period of unrestricted and restricted access to the water trough.

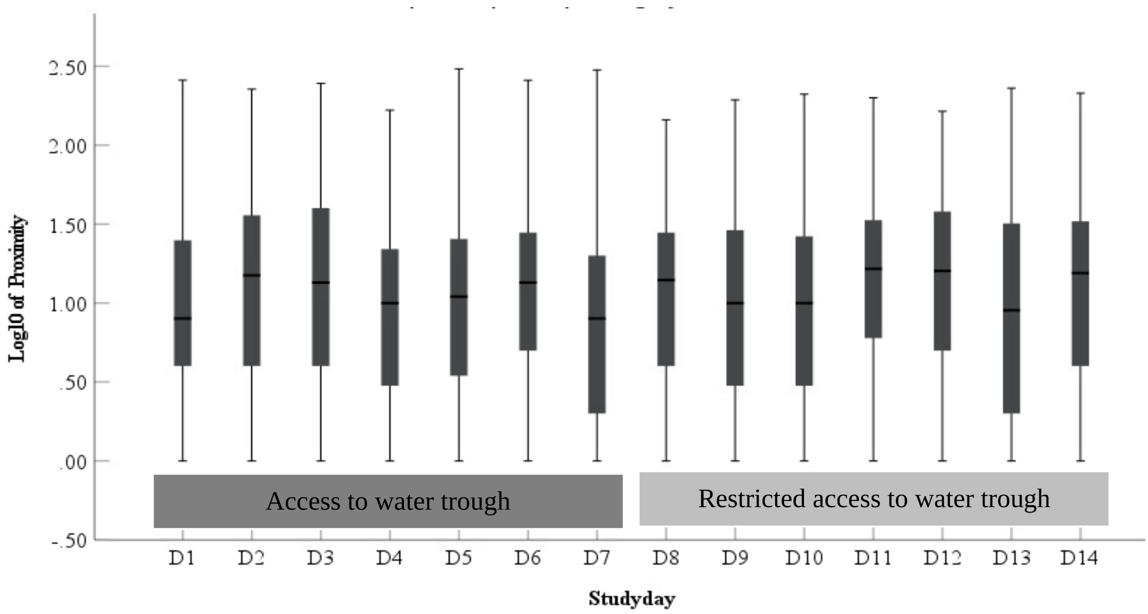

Figure 17 Boxplot of log_{10} transformed duration (sheep minutes) during each day that sheep were estimated to be within 3m of camera locations.

Camera location influenced the duration that sheep spent in proximity to the camera ($p < 0.001$). Sheep spent more time within 3m of Camera 1, Camera 11 and Camera 14 and less time near Cameras 6, 7, 8 and 10 ($p < 0.05$; Fig 18).

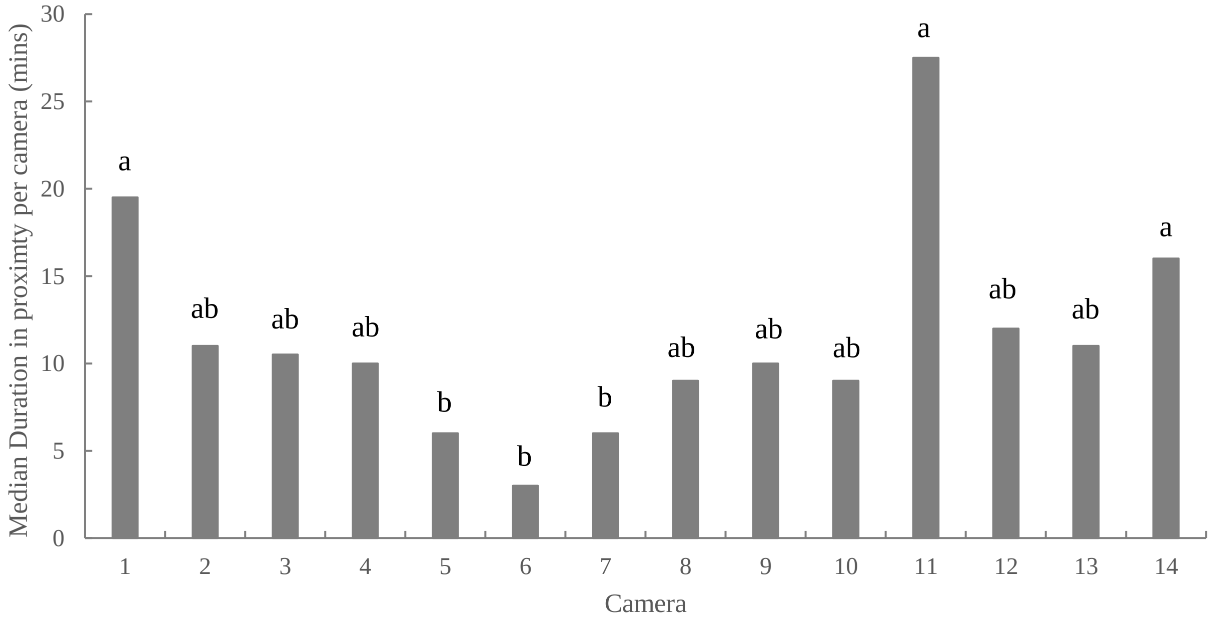

Figure 18 Median duration (in sheep minutes) that sheep were detected within 3m of each camera location during the observation period in autumn. ^{a,b} ***Values with different superscripts are significantly different (p<0.05).***

Time of day did not influence the duration that sheep were in proximity of the camera locations ($p < 0.05$; Fig. 19).

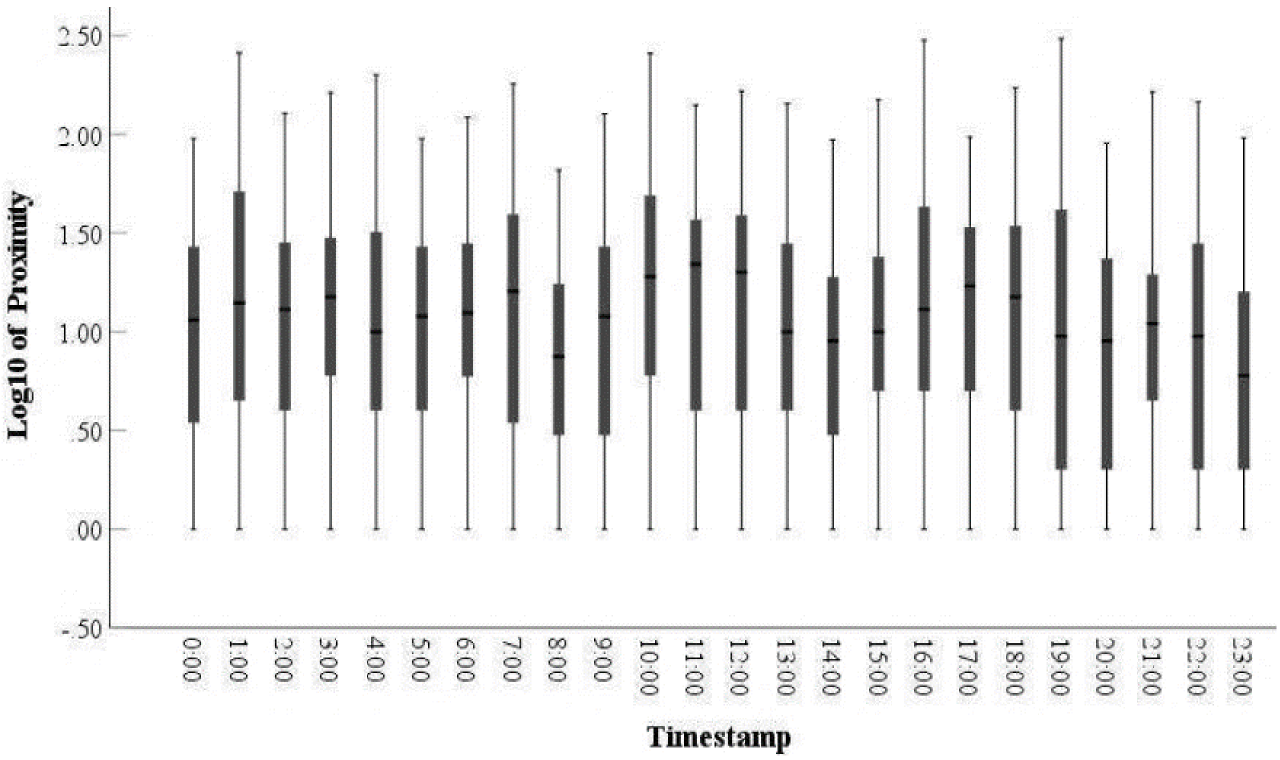

Figure 19 Boxplot of the duration (log$_{10}$) sheep were estimated to be within 3m of each camera location by time of day.

3.4.5 GPS locations

The stream zone area accounted for 0.23ha (7.9%) of the 2.94 ha paddock area. During the period of unrestricted access to the trough there were 702 GPS locations recorded in the stream zone (1.01%) and 64397 in the remainder of the paddock (98.99%). During the period when access to the trough was restricted there were 630 locations in the stream zone (1.74%) and 36217 in the remainder of the paddock (98.26%). The number of GPS locations was lower in the stream zone than the rest of the paddock than was expected due to chance ($p < 0.001$).

During the unrestricted trough period, there was a hotspot ($p < 0.05$) identified along the flat north/northeast area of the paddock which indicates that sheep spent more time in this area than on average (Fig. 20A). During the period when there was restricted access to the water trough there were hotspots ($p < 0.05$) identified on the flat south/southwest areas of the paddock and the flat north/northeast area of the paddock (Fig. 20B). A hotspot analysis of the 3 m stream showed that when access to the trough was unrestricted there were hotspots near each culvert and in the area around Camera 5 ($p < 0.05$; Fig. 20C). Restricted access to the water trough resulted in hotspots in the stream zone being identified at both culverts and within the stream zone near Camera 9, 10 and 13 ($p < 0.05$; Fig. 20D).

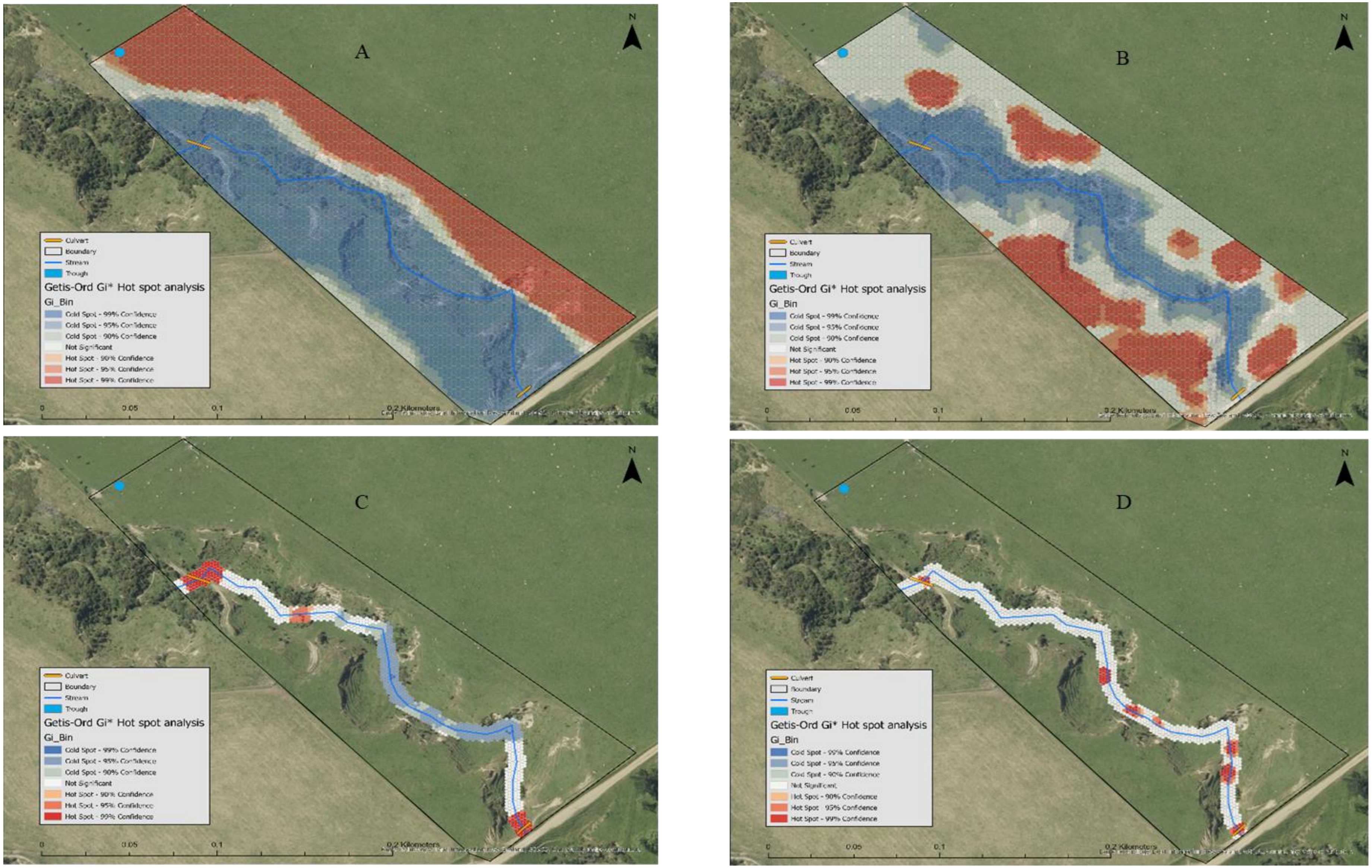

*Figure 20 Getis-Ord *GI optimized hotspot analysis. A hotspot is an area that has a greater concentration of sheep location clusters compared to the expected number given a random distribution of sheep clusters. Fig 20A is unrestricted access to trough. Fig 20B has restricted access to the trough. Fig 20C is the riparian zone (3m either side of the stream) with unrestricted access to the trough. Fig 20D is the riparian zone with restricted access.*

3.4.6 Stream flowrate and quality

The water flow rate at both the inflow and outflow monitoring locations of the stream was not normally distributed ($p < 0.001$; Fig. 21). Flow rate was higher at the outflow compared to the inflow monitoring site ($p < 0.001$). On D7 the water flow rate of the stream was greater than on D6 ($p = 0.019$). Similarly, flow rate was greater on D13 compared to D14 ($p = 0.016$). Stream flow rate did not differ trough access periods ($p = 0.758$).

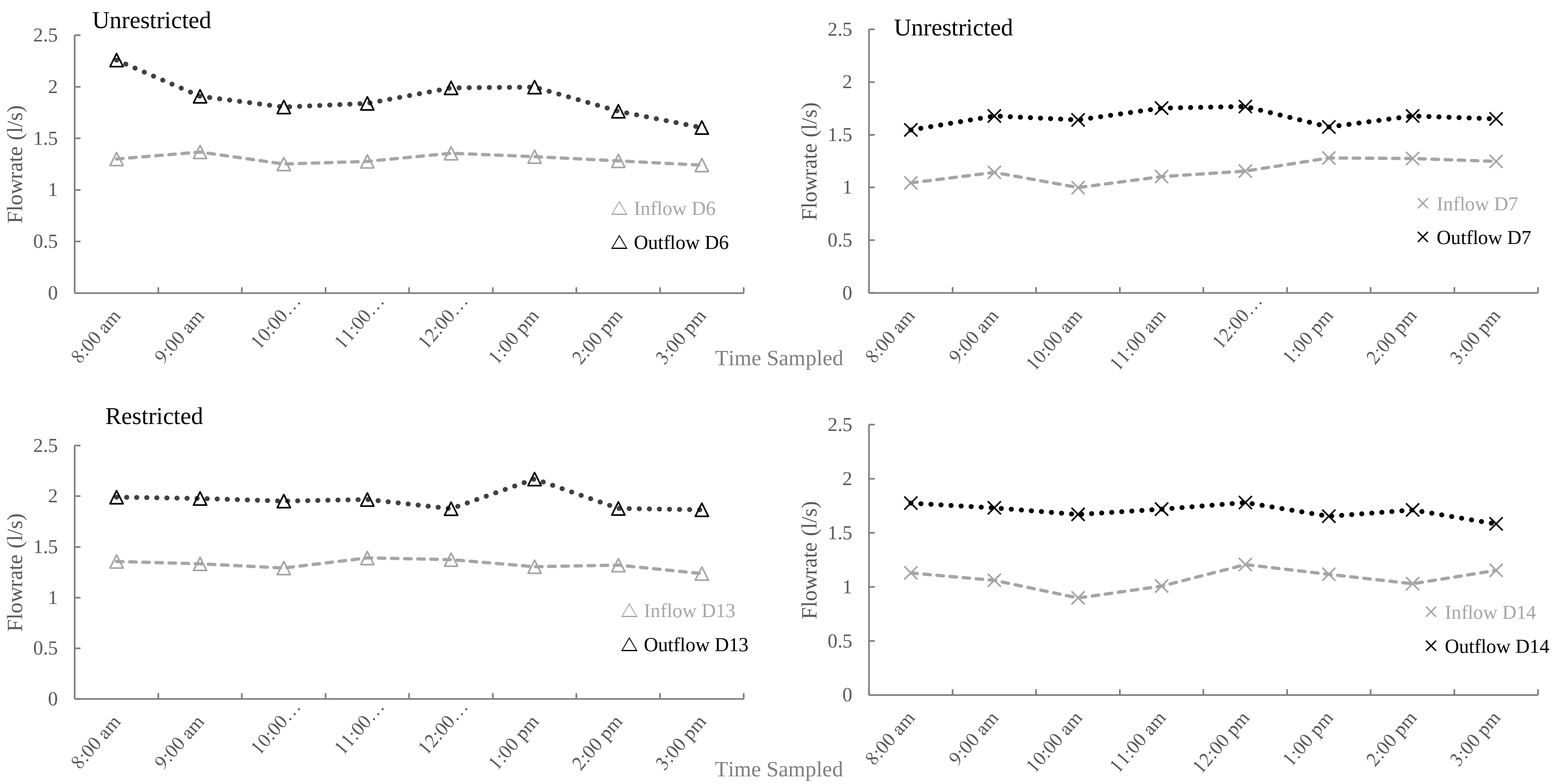

Figure 21 Stream water flow rates at each sampling time at the stream inflow (grey line) and outflow (black line) monitoring sites on D6 (△, 12 April 2021) and D7 (×, 13 April 2021) when access to the trough was unrestricted and on D13 (△, 19 April 2021) and D14 (×, 20 April 2021) when access to the water trough was restricted.

Table 11 Mean, median and interquartile range (in parentheses) of the concentrations of suspended sediment (mg/l), total nitrogen (mg/l), total phosphorous (mg/l), ammonium (mg/l) and E. coli (cfu/100 mL) in water samples collected on study days D6, D7, D13 and D14. NA indicates that concentrations were below the detectable limit of the analytical method.

	Unrestricted Trough		**Restricted Trough**		**Significance**	
	D6	D7	D13	D14	Treatment	Inflow/Outflow
Suspended Sediment (mg/l)	2.82, 2.28 [a] (0.990, 3.209)	2.68, 1.47 [b] (0.894, 3.312)	5.07, 4.06 [a] (0.955, 7.483)	7.21, 5.72 [a] (2.161, 9.342)	p = 0.002	p = 0.697
Total Nitrogen (mg/l)	0.48, 0.46 [a] (0.289, 0.569)	0.60, 0.57 [b] (0.530, 0.716)	0.52, 0.53 [a] (0.440, 0.585)	0.49, 0.46 [b] (0.418, 0.568)	p = 0.390	p = 0.076
Total Phosphorus (mg/l)	0.026, 0.012 [a] (0.016, 0.024)	0.025, 0.022 [a] (0.015, 0.032)	0.024, 0.022 [b] (0.015, 0.032)	0.021, 0.018 [a] (0.012, 0.033)	p = 0.856	p < 0.0001
Ammonium (mg/l)	NA	NA	0.85, 0.85[a] (0.780, 0.929)	0.85, 0.85 [a] (0.730, 0.860)	NA	p = 0.008
E. Coli (cfu/100ml)	1302, 320 [a] (155, 1235)	965, 255 [a] (230, 1410)	626, 345 [a] (155, 935)	330, 330 [a] (120, 2050)	p = 0.489	p < 0.0001

[a,b] Medians with different superscripts are significantly different (p < 0.05)

3.4.6.1 Suspended Sediment

Water suspended sediment concentrations did not differ between the inflow and outflow sampling sites ($p = 0.697$; Fig. 22). Suspended sediment concentrations (SSC) differed between D6 and D7 ($p = 0.022$) but not between D13 and D14 ($p = 0.895$; Fig. 22). SSC were higher when sheep were restricted from accessing the water trough ($p = 0.002$; Table 11). Suspended sediment loads (SSL) did not differ between sampling locations ($p = 0.687$) but were greater when access to the water trough was restricted ($p = 0.002$). SSL did not differ between study D6 and D7 nor between D13 and D14 ($p = 0.3456$, $p = 0.895$, respectively). There was no relationship of water sediment with *E Coli* loads ($R^2 = 0.1742$, $p = 0.417$).

3.4.6.2 Nitrogen

Total nitrogen concentrations (TNC) and total nitrogen load (TNL) did not differ between water trough access treatments ($p = 0.390$, $p = 0.629$, respectively; Fig. 23). TNC differed between D6 and D7 ($p = 0.02$) but not between D13 and D14 ($p = 0.450$). TNL did not differ between D6 and D7 ($p = 0.200$)

but tended to be higher on D13 than D12 ($p = 0.060$). TNC did not differ between the inflow and outflow sampling site ($p = 0.076$) whereas TNL was lower at the inflow compared with the outflow site ($p = 0.0002$).

On D6 and D7 ammonium concentrations were below the detection limit of the analytical method. These data could not be analysed statistically due to a lack of data. On D13 and D14 the ammonium concentration did not differ between days ($p = 0.1806$), but the ammonium load was greater on D13 than D12 ($p = 0.0005$). On both D13 and D14, ammonium concentrations were higher at the outflow than inflow sampling site ($p = 0.0003$ and $P=0.0001$, respectively).

3.4.6.3 Phosphorus

TPC were higher at the inflow sampling site compared with the outflow ($p < 0.001$; Table 11). TPC did not differ between sampling day 6 and 7 ($p = 0.896$) or D13 and D14 ($p = 0.509$). TPC did not differ between trough access treatments ($p = 0.856$; Fig. 24). Total P load (TPL) did not differ between D6 and D7 ($p = 0.792$) but was higher on D13 compared to D14 ($p = 0.022$). TPL did not differ between trough access treatments ($p = 0.989$) but was higher at the inflow compared with the outflow sampling site ($p < 0.001$). There was a tendency for a correlation between TPL and SSL ($R^2 = 0.022$, $p = 0.088$).

3.4.6.4 E. Coli

Both *E. Coli* concentration and load was higher at the outflow sampling location compared to the inflow location ($p < 0.0001$ and $p < 0.0001$, respectively). *E. Coli* concentrations and loads did not differ between trough access treatments ($p = 0.489$ and $p = 0.5280$, respectively) or between sampling days during each treatment ($p = 0.706$ and $p = 0.429$, respectively; Fig. 25).

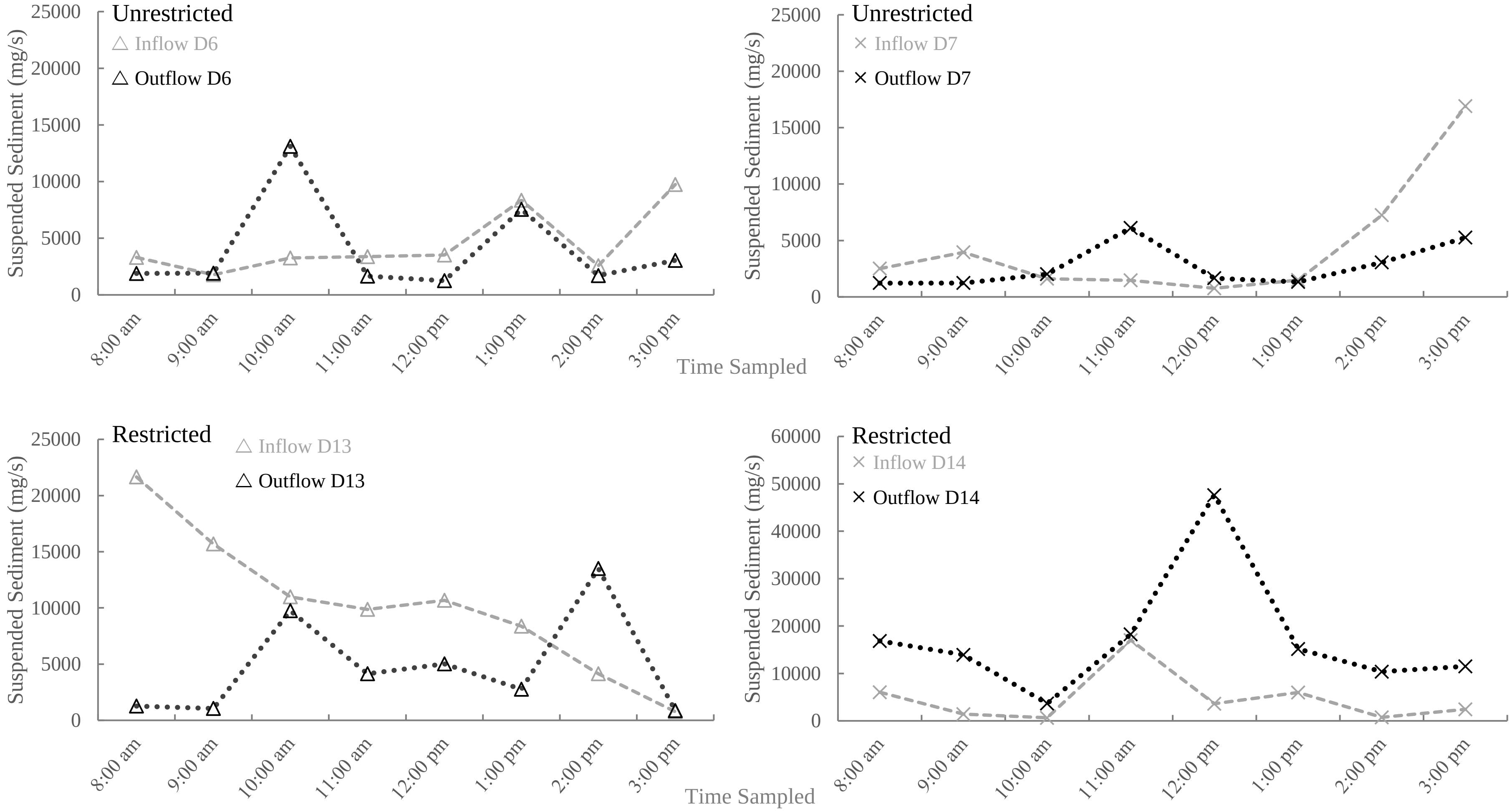

Figure 22 Suspended sediment load (mg/s) in water samples collected at the inflow (grey line) and outflow (black line) sampling sites on D6 (△, 12 April 2021) and D7 (×, 13 April 2021) when access to the trough was unrestricted (left) and D13 (△, 19 April 2021) and D14 (×, 20 April 2021) when trough access was restricted. Note: Y axis scale is different between each treatment and each graph.

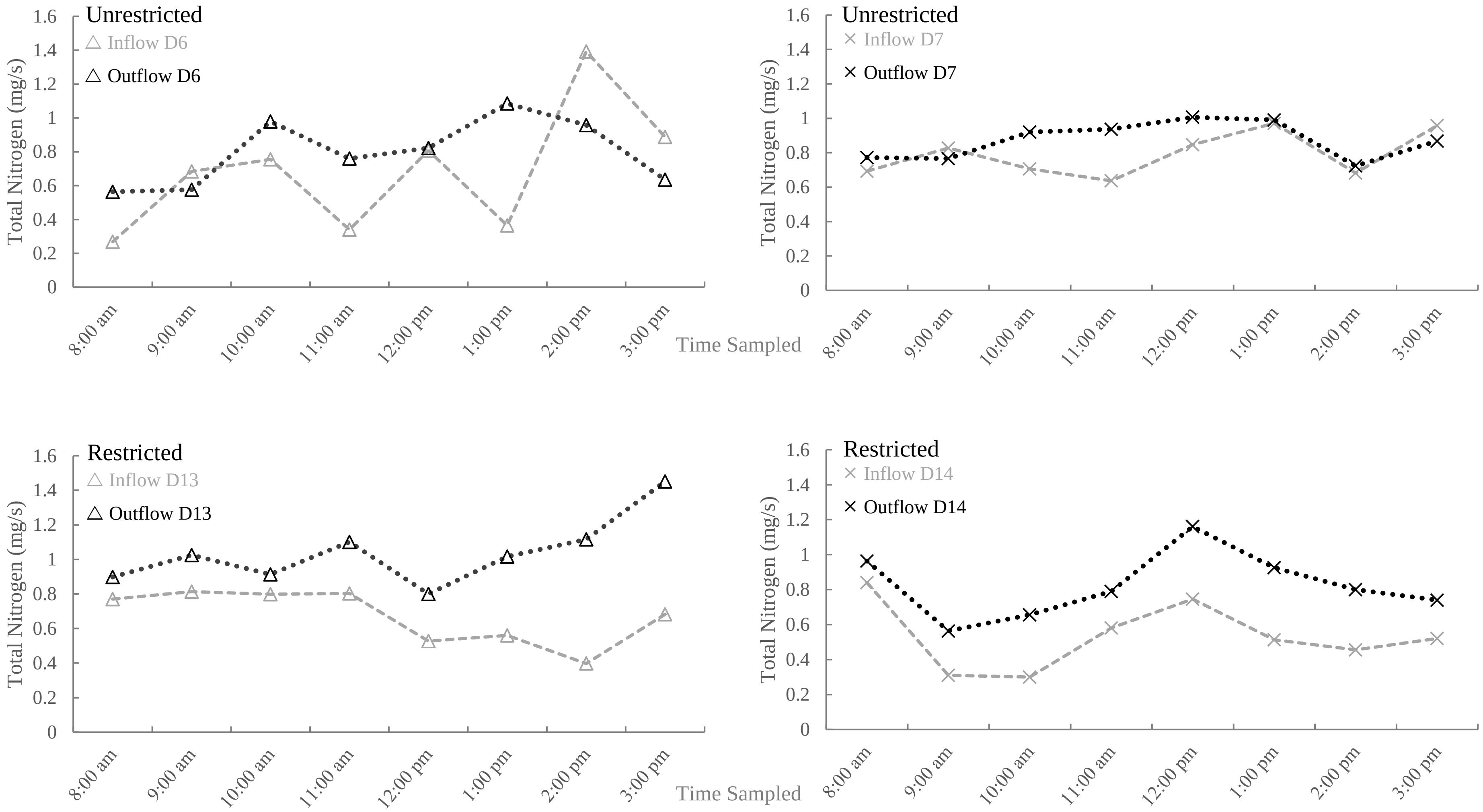

Figure 23 Total Nitrogen load (mg/s) in water samples collected at the inflow (grey line) and outflow (black line) sampling sites on D6 (△, 12 April 2021) and D7 (×, 13 April 2021) when access to the trough was unrestricted (left) and D13 (△, 19 April 2021) and D14 (×, 20 April 2021) when trough access was restricted..

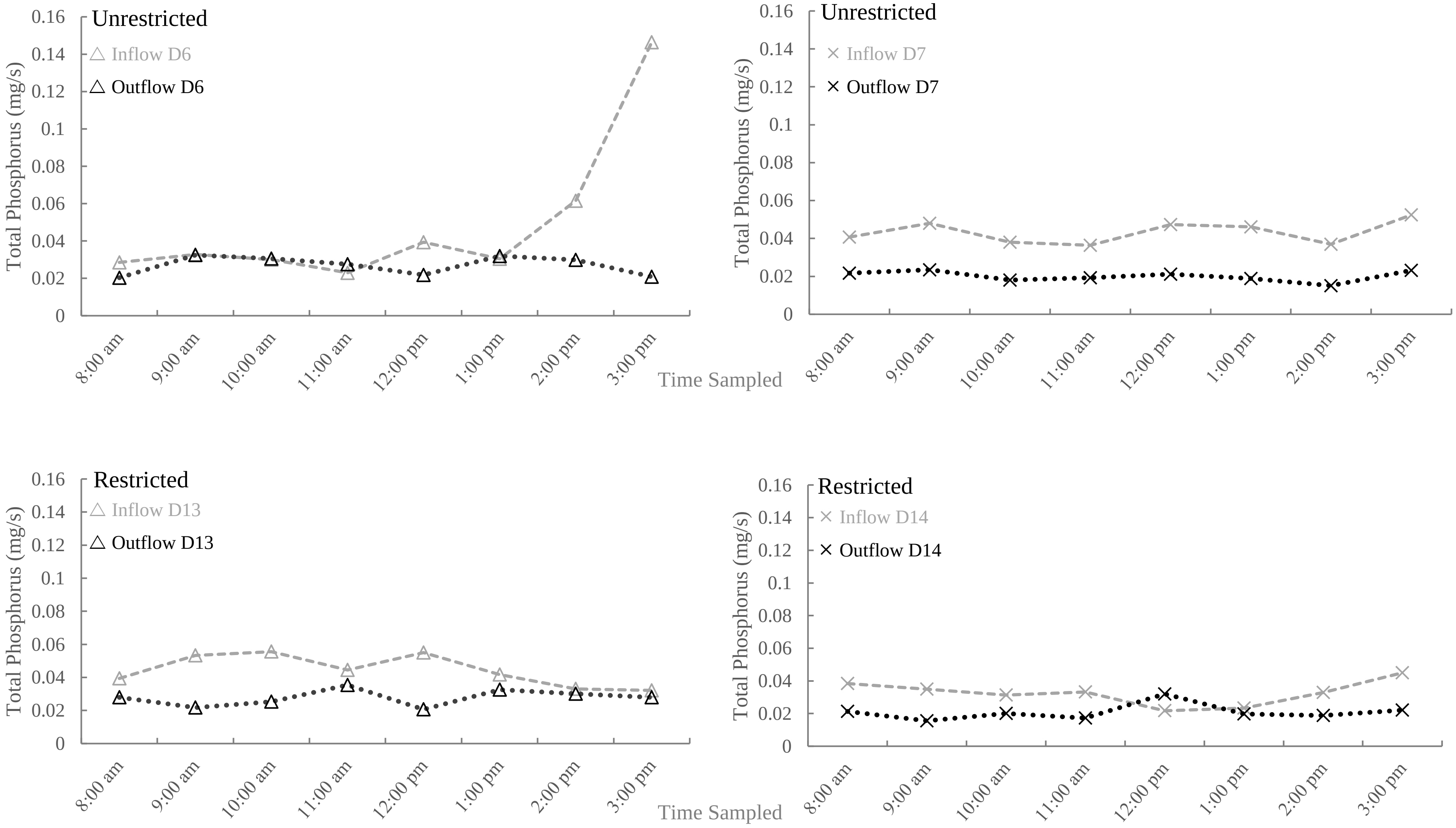

Figure 24 Total Phosphorus load (mg/s) collected at the inflow (grey line) and outflow (black line) sampling sites on D6 (△, 12 April 2021) and D7 (✕, 13 April 2021) when access to the trough was unrestricted (left) and D13 (△, 19 April 2021) and D14 (✕, 20 April 2021) when trough access was restricted.

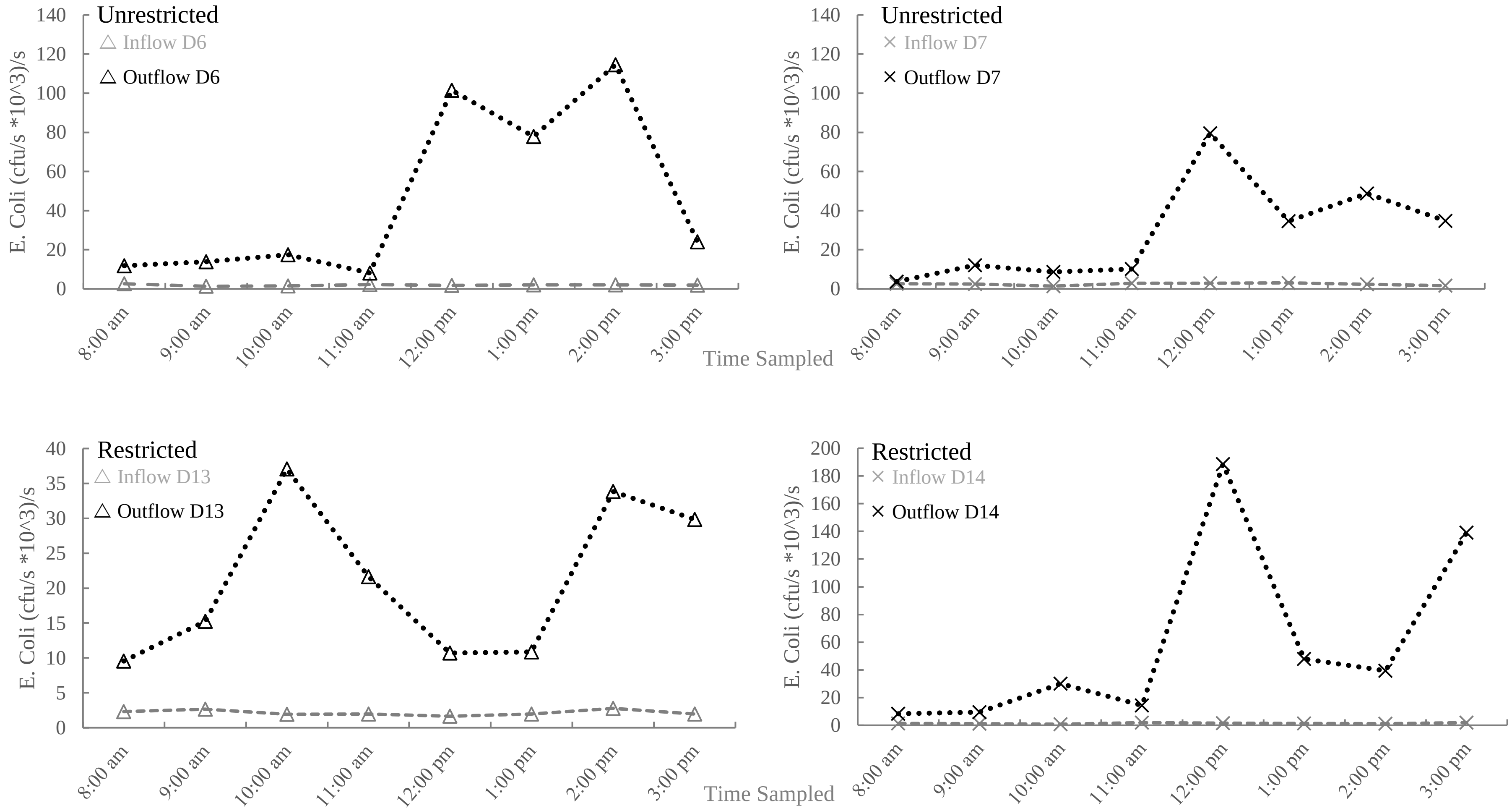

Figure 25 E Coli (cfu/s *10^3/s) collected at the inflow (grey line) and outflow (black line) sampling sites on D6 (△, 12 April 2021) and D7 (×, 13 April 2021) when access to the trough was unrestricted (left) and D13 (△, 19 April 2021) and D14 (×, 20 April 2021) when trough access was restricted. Note: Y axis scale is different between treatments and graphs.

3.5 Discussion

The aim of the current study was to determine how sheep interact with a natural waterway and what impact their interaction has on measures of water quality. It was hypothesised that the frequency of sheep interacting with the stream, and drinking from it, would increase when access to the trough was restricted compared to when sheep had access. It was also predicted that labile nutrients within the soil matrix would generate degraded water quality metrics as a result of increased rainfall events that generally occur in Autumn.

In the current study, hotspot analysis of sheep GPS locations showed that sheep showed a spatial preference for non-stream zone areas of the paddock and clustered in the flatter areas. Sheep that were seen within 3m of the stream spent most of their time grazing. Previous studies have reported that sheep not only avoid flowing or standing water but also the riparian zones of a waterway (Collins et al., 2007). It would be expected that as a result of decreasing daylength and pasture quality in autumn (Penning et al., 1991) the duration sheep spend grazing each day would increase (Gonyou, 1984). Riparian areas are often more fertile than non-riparian areas of a paddock as seasonal flooding leaves behind fertile fine-grained sediments which support pasture production (Blankenberg & Skarbøvik, 2020). The increased pasture growth may, therefore, encourage preferential grazing of livestock within the stream zone a finding which was supported in the current study and by Collins et al. (2007). It is critical to note, however, that the sheep spent proportionately less time in the stream zone relative to the rest of the paddock and the sheep that did enter the stream zone did so to mainly graze. The impact that sheep had on stream bank erosion was not measured but if time spent in an area was indicative of erosion potential, then their impact would be minimal.

During the period of restricted water trough access additional hotspots were identified near camera positions nine and ten within the stream zone, as well near the culverts that were not observed when access to the trough was unrestricted (Fig. 20C). The slope in these areas varied between 7 and 20° and access to these areas was from the flat areas above (> 20°) (Chapter 2.2, Fig. 1). The proximity to cameras of sheep to camera locations nine and ten also increased during this period when access to the trough was restricted compared with unrestricted which suggests that the sheep spent more time in this area of the stream zone. Video footage from these cameras, however, did not show any additional behavioural events. This may have been the result of sheep either; being out of view of the camera but still within the range of the accelerometers or being outside the stream zone. The foraging location and dietary choices of sheep can be influenced by the distance between flock peers and the preferred feeding site, as well the size of their own group (Dumont & Boissy, 2000). The hill slope may have encouraged increased activity in these areas compared to other regions of the paddock due to the ease of accessibility.

The number and duration of sheep behaviour events within the stream zone did not change between trough access treatments or days. Sheep were observed to drink from the stream at four of the camera locations (5, 6, 8, 13), with drinking bouts varying considerably from 3.6 seconds to 33 seconds in length. It is worth noting that only two sheep were recorded drinking from the stream and the same two exhibited all of the drinking behaviours recorded across the four camera locations. Drinking from the stream was an infrequent behaviour exhibited by the sheep during autumn. Filipčík et al. (2020) noted that sheep drinking made up only a small proportion of the total number of records of daily activities in their study and ranged from 0.10% to 0.20% of the total time. Under the conditions of the current study direct interaction with the stream was not influenced by the presence of an alternative water source (trough). This suggests that access to a reticulated water system within a paddock may not necessarily result in sheep drinking from it nor did its presence alter sheep behaviour or interaction with the stream. Sheep behaviour is affected principally by factors related to variations in climate and the availability of adequate nutrition (Goddard et al., 2006). Environmental factors that may affect sheep behaviour include declining sward height and increasing frequency of rainfall (Champion et al., 1994). This experiment provided two water sources a trough and a stream, however, the infrequent use of these sources suggests that the pasture may have contained enough moisture to satisfy their requirements.

The frequency of walking in the waterway varied greatly between individual sheep in the current study. Further research is warranted to understand if the preference for walking in waterways is learnt or if maternal or paternal influence can be passed on to the lamb. This could mean that early training of sheep to a waterway, or culling based on a sheep's observed interest, could create a flock that avoids streams. Research of cattle has shown that providing an alternative water source is an incentive to move cattle away from water channels in the United States (Collins et al., 2007). However, under extensive stocking conditions in New Zealand, alternative water sources located on hilltops did not reduce the use of streams by beef cattle (Collins et al., 2007).

During the current study the median duration sheep were in the stream zone increased either following a rainfall event (D5 and D10), or during the event (D4 and D10). This finding was in agreement with Champion et al. (1994) who suggested there was an interaction between rainfall and time spent grazing. They reported that heavy rain (greater than 1 mm/hr) during a peak grazing time reduced grazing activity and caused the grazing pattern to be modified. In New Zealand, Autumn is characterised by an increase in rainfall events, cooler temperatures, and shorter days compared with summer. In hilly areas, up to 95% of the water in streamflow has either passed over or through a hillside and its soil before reaching the channel network (Bronstert & Plate, 1997). Water quality was not tested during the days when the effect of rainfall on ewe behaviour was observed. It would be interesting to determine if there was a correlation between the increased sheep presence and a degradation in water quality. Due to the slope of the hills intercepting rainfall and providing shelter the sheep in the current study may have spent more time within proximity to the stream compared with the exposed flatter areas at the top of the paddock.

E coli loads in the current study were higher at the outflow site compared to the inflow which indicates that the sheep grazing in the paddock were the likely source. *E. coli* loading rates on sheep pasture have been found to be higher than cattle pasture at typical stocking densities (Collins et al., 2007). The survival of bacteria within animal faeces is influenced by moisture content, temperature, pH, nutrients, the animal's diet, bacterial strain and solar radiation (Moriarty et al., 2011). Grazing sheep on hill country could therefore pose a risk to water quality as they have higher *E. Coli* loading rates compared to cattle and high pathogen survival in faecal deposits. In the current study sheep were not observed to defecate or urinate directly into the stream. In comparison in New Zealand, beef cattle on hill country have been observed to defecate in the riparian zone at a rate of 0.2 faeces per cow per day with half of the faeces deposited directly into the water (Bagshaw, 2002). It would be expected as a result that sheep would have a lesser impact on the microbial contamination of streams that cattle. Sheep dung contains *E. Coli* concentrations of 1.62×10^7 per g of fresh faeces (Moriarty & Gilpin, 2014) compared to cow faeces which had a predicted *E. coli* concentration in streams draining hill country farms at 1.3×10^9 per head of cattle per day (Collins & Rutherford, 2004). Microbes not inactivated or retained by soil are susceptible to leaching, as water flowing through soil from irrigation or rainfall causes microbial movement (Aislabie et al., 2011). Soil moisture is one of the important factors influencing pathogen survival in soil with survival more likely when soils are moist (Saini et al., 2003). Given that autumn is typically cooler, and four rainfall events occurred during this study, the survival and transport of *E coli* from fresh and aged sheep faeces to the stream was likely to have led to the measured deterioration in water quality.

During this study, total N loads where higher at the outflow than inflow site. This indicates that there was sufficient rainfall to move nitrate through the soil into the stream and the soil colloids retained N for plant growth or microbial respiration. In streams, N enters mainly as dissolved inorganic (NH_4^+, NO_2^-, NO_3^-) and organic forms (McDowell & Wilcock, 2008). Increased soil aeration mixes readily available carbon and N sources with soil organisms resulting in a flush of mineralisation and nitrification and under such conditions nitrate-N accumulates in the soil (McLenaghen et al., 1996). Nitrate leaching represents the single greatest loss of N from the soil and plant system (McLenaghen et al., 1996). If plant growth in streams demand for N exceeds supply then NO_3^- concentrations may be negligible (McDowell & Wilcock, 2008). Stream N concentrations may be diluted by large surface runoff (McColl & Gibson, 1979) and the increase in stream flow could explain the low values. As soil moisture increases, nitrate is flushed from the soil, causing concentrations in streams to increase to a maximum value in mid-winter (McDowell & Wilcock, 2008).

To improve the management of our natural resources, a potential management strategy that sheep farmers could use to actively manage the paddocks could be to identify critical nutrient areas and to observe sheep distribution within those areas. The negative water quality impacts that were observed following a rainfall event which may in part be related to the presence of grazing sheep but may also be linked to the wider nutrient movement within the farmed landscape. As nutrients already exist within the soil sphere, moving sheep off paddocks with streams prior to a rainfall could reduce contaminant loss, although this may not be practical in some farm systems and will only mitigate the direct influence that sheep exhibit. Rather, maintaining the environment directly surrounding the stream through plant diversity, sward management through grazing and managing significant nutrient loss areas would be more appropriate.

3.6 Conclusion

The behaviour of sheep around the stream during Autumn in the Manawatu was not influenced by the availability of a drinking trough. Access to a trough had a negligible influence on the sheep's occupation of the stream zone. It is probable that the moisture content of the pasture was sufficient to satisfy the water requirements of the sheep during the trial and negated the likelihood of drinking events. Water quality impacts were elevated during rainfall events but there was not a significant correlation between the sheep and a decline in water quality. There were no recorded instances were sheep defecated into the stream. This study suggests that there was a not a significant influence of sheep on water quality and any effects were likely due to a rainfall event.

Chapter 4 General Discussion

The experiments in this thesis examined the behaviour of sheep around a natural waterway when access to a reticulated water trough was restricted and unrestricted. In addition, they assessed the impact sheep behaviour had indicators of water quality of the stream. It was hypothesised that during summer, when sheep did not have access to the trough, they would spend more time in and around the stream zone and that water quality metrics would be elevated as a result. During autumn it was hypothesised that as nutrients stored within the soil matrix would be more mobile due to rainfall events baseline water quality metrics would be greater than in summer and that sheep without access to the trough would interact within the stream zone more often than when access to the water trough was unrestricted.

The results of these studies showed that the primary behaviour of sheep observed within the stream zone during summer was grazing (61.0%), stream interaction (behaviours within 1m of the stream) (13.2%) and walking in the stream (13.0%). Similarly, during autumn, grazing was the dominant behaviour (62.2%) with stream interaction and walking in the stream accounting for 15.8% and 14.8% of the behaviours recorded. Drinking behaviour was infrequent and accounted for 0.9% of the recorded behaviours during summer and 0.2% in the Autumn. Al-Ramamneh et al. (2012) reported that sheep spent approximately 0.2% of each 24 h day drinking, although, in the current study video recordings were triggered by motion thus there was the potential that not all drinking behaviours were recorded. Furthermore, rather than an observational study over 24-hour periods from the entire area, results from the current study were generated from drinking behaviours were based on footage captured by cameras at located along the stream path.

The study site of the experiments in this thesis contained a stream zone (3 m either side of the stream) that accounted for 7.87% of the total land area of the paddock (0.23 of 2.94ha). When access to the water trough was restricted, there was a corresponding increase in the number of GPS data points located within the stream zone from 0.63% to 2.97% compared with the period that the trough access was unrestricted. The increase in GPS locations was smaller in autumn from 1.1% to 1.74% between periods of unrestricted and restricted access. Access to the trough, however, did not influence the duration or frequency of behaviour bouts in which sheep interacted, walked in, or drank from the stream. This finding is contrary to that of McCoard et al. (2020) who reported that when multiple drinking sources were available the estimated water intake per ewe was 2 to 3-fold greater than when there was a single trough. Similarly, the results of the current studies contradict the findings of Chikwanha et al. (2021) who reported that exclusion fencing at open water points limited access by sheep and facilitated off-stream watering (Chikwanha et al., 2021). In the current study the stream transected the paddock and was accessible along most of the stream's length. Thus, it appears that the readily available access to the stream water was not a significant stimulus to alter sheep behaviour. Similarly, the accessibility to a trough did not influence the grazing behaviour of sheep around the stream with less time in the stream zone than the remainder of the paddock. Thus, in the conditions of the current study it would have been unnecessary for fenced exclusion of the stream to reduce sheep duration spent in the stream and their potential impact on water quality.

The moisture content of the pasture in the study site was lower during summer than autumn. The moisture content ranged from 53.52 to 71.7% during summer and 79.8 to 90.72% during autumn. Research has shown that during some periods of the year the water contained in pasture can meet the water requirements of sheep without negative impacts on performance (Dove et al., 2000). The water intake of sheep is partly met by the water contained in feed, which can be as low as 5% in dry feeds to as high as 90% in fresh grasses and legumes (Chikwanha et al., 2021). A high water content of herbage is positively correlated with high dry matter digestibility and negatively correlated with the proportions of dead plant material (Radcliffe, 1982). Water intake is positively correlated with dry matter intake (Chikwanha et al., 2021). This may trigger an upsurge in the animal's propensity to drink water while feeding. Where moisture is available for growth, pasture grazed by sheep is able to adapt to defoliation and produce new growth of higher quality (Rennie et al., 2014) which results in more pasture available to be grazed. During summer and autumn, pasture litter can comprise over 50% of herbage mass (Radcliffe, 1982). Therefore, forage selection by sheep may vary throughout each season depending on the herbage mass relative to different stratification based on slope, sunlight interception and nutrient availability of a paddock. A possible mechanism for this forage selection may be leaf length. Tiller selection for grazing is affected by herbage mass, tiller quality and extended tiller height (Baumont et al., 2004). The grass next to the stream may have longer tillers and more water for continued growth, however, it appears that in the current study this appeared to insufficient incentive until the pasture in easily accessed locations was depleted.

Accelerometer proximity data within the stream zone during summer and autumn was greater in the crepuscular periods of early morning (04:00-06:00) and late evening (20:00-22:00) than the rest of the day. In warm environments sheep forage during the cooler hours of the day when temperatures are low. This behaviour can minimise body water loss through the utilisation of dew obtained from foraging and maintaining water balance through evaporative cooling (Chikwanha et al., 2021). A plant's ability to transpire is limited by nocturnal cooling (Monteith, 1956), therefore, it is likely that during the early morning and late evening periods plants contain more moisture during the night when compared to the day. By harvesting moist forage near to the stream during cooler periods, sheep may be able to gain sufficient water from the grass and improve water use by reducing the energy requirements associated metabolic processes. A management method to reduce the impact of sheep on stream water quality would be to remove the sheep from the stream during these periods and only grazing the paddock during the day. Placing sheep in a runoff paddock with a trough could encourage the sheep to commence all their drinking during this time.

During both summer and autumn, pasture masses measured along the flat areas of the paddock surrounding the gully decreased during study period. The flat areas of the paddock (<10°) showed significant GPS location hot spots with significant cold spots in the steep and very steep areas (>25°) adjacent to the stream showing sheep spent less time in these areas compared to the flat areas. The location of the hot spots was likely due to the flat areas containing forage that was easier to access than the steeper regions of the paddock. López et al. (2003) reported that during summer in the Manawatu region of New Zealand ewes grazed low (1–12°) and medium slope areas (13–25°) more frequently than steep or very steep areas (>25°) where herbage was highest. The steeper regions of the paddock may have been less desirable for grazing due to difficult accessibility, reduced forage availability and forage composition. A strong relationship exists between sheep grazing behaviour and herbage accumulation rate throughout the year that shows increased grazing activity on steeper slopes when herbage accumulation rates across flatter microsites are low (López et al., 2003). Sheep have been shown to use the angle of the slope as a filter of forage selection favouring less angled areas for preferential grazing over steeper regions of a paddock (Heitschmidt & Stuth, 1991). Herbage accumulation rates have been reported to decrease with increasing slope as flatter areas can produce up to twice as much herbage as hillsides (Lambert et al., 1983; Radcliffe, 1982). In the current studies, the stream was at the bottom of a gully surrounded by steep slopes, therefore it is plausible that there was difficulty for sheep to gain access to the stream zone compared to the flat regions of the paddock and culvert areas. Thus, it is likely that sheep spent less time in those areas. When pasture mass on the flatter areas began to decrease, however, sheep were more likely to explore steeper areas of the paddock. Generally areas close streams are steeper land classes with low pasture growth (Tran et al., 2022). Hill country streams form through the complex interplay of surface and subsurface hydraulic erosion processes (Marden et al., 2012), cutting down through the landscape over time, and as such, they are often found in steep sided gullies. The presence of gullies may be a deterrent to sheep accessing the stream due to difficulty in traversing the terrain. This explains in part, why there were significant cold spots created around the steep areas of the paddock and as the trial progressed, hotspots were created in previously less desirable areas based on slope. A management tool to reduce sheep accessing steep areas could achieved by farmers leaving longer residual pasture and removing sheep before the pasture mass declines enough to result in sheep moving into steeper areas of the paddock.

During the summer study, the flow rate of the stream was higher at the outflow measurement site due to a rain event on D7. In autumn, stream flow rate was also higher at the outflow than inflow water sampling site and differed between the two sampling days of each trough access period (between D6 and D7, and D13 and D14). During the autumn experiment, 47.5 mm of rainfall was recorded on five study days (D3, D4, D7, D9 and D10) whereas in summer there was 26.7 mm of rain on two days (D1 and D7). Streams intercept water flow derived from rain falling within its catchment area and generating surface and subsurface runoff. As stream order increases, the length of the stream and the area of the drainage catchment also increases (Matsuda, 2004). Water may infiltrate the soil system and come to the surface in an intermittent or ephemeral channel before entering the perennial channel (Hewlett & Hibbert, 1967). Buck et al. (2004) found that ammonium and TN concentration were positively correlated with flow rate in summer. Nutrients mobilised during a rainfall event will likely increase the concentration in the water tested. As each rainfall event would have influenced the hydrological processes within the paddock, the variation in rainfall could explain the difference in flow rate and nutrient loads across each sampling day.

In the summer experiment, stream water total nitrogen load was higher when sheep were restricted from accessing the trough, but no differences were seen in autumn. In addition, in both summer and autumn ammonium and nitrate-N loads were higher at the outflow than inflow sampling site. In summer TNL, NH_4 and NO_3 were elevated as the result of rainfall event on D7. In autumn, TNL did not differ between treatments but was lower at the inflow sampling site. In water bodies, nitrogen as nitrate-N and ammonium, shows seasonal variation due to their mobility in biological and soil systems (McColl & Gibson, 1979). Nitrate ions are freely mobile in the soil solution and are, therefore, at high risk of leaching below the root zone as water moves through the soil. Ammonium ions, however, tend to be retained by the soil through cation exchange mechanisms and are more likely to be mobilised in surface runoff (Hooda et al., 2000). Nutrient concentrations may be lower in winter, and spring compared to summer and autumn, due to dilution by large volumes of runoff. Increased rain and runoff events associated with the wetter seasons, however, may increase concentration of nutrients mobilised into waterways. Low nutrient concentrations in spring may be explained by nutrient uptake during vigorous growth of vegetation. Buck et al. (2004) found that in New Zealand, median nitrate-N and ammonium concentrations were highest during May. In addition, during summer approximately 33% of TN was exported as nitrate-N or ammonium compared to 80% during late autumn. The different seasons influenced the concentration of nitrogen in the water tested, which was likely the result of the interconnected hydrological pathways moving nutrients around. The presence of the sheep within the paddock may have contributed to the N loads through urination across the trial site but direct deposition into the stream was not observed.

During the summer and autumn studies, there was little evidence that the sheep directly influenced the inorganic nitrogen load in the stream water. Sheep were observed to primarily graze the riparian zone and occasionally directly interacted with the stream. The presence of livestock near streams and within the riparian zone can dislodge sediment and walking tracks which result in pathways can allow sediment and excrement to enter waterways (Aarons & Gourley, 2013). Sediment-driven fluvial processes (sheet erosion) during summer, therefore, could be responsible for the TN detected in water samples in the current study. Sediment is mobilised during periods of high flow and is deposited during periods of low flow (Vale et al., 2016). Soil surface treading damage in riparian areas may also be a source for the export of sediment and nutrient (Butler et al., 2008). Animals defecating and urinating across a landscape will result in different pollutant sources and propensity to degrade waterways (Aarons & Gourley, 2013). Any rainfall in these areas is likely to wash contaminants directly into the stream. Sheep spending time in these areas increase the risk of impacts on water quality. As stream baseflow levels begin to increase in autumn, the build-up of nutrients within the soil during the summer are then mobilised increasing the loads measured. Due to the time lag associated with water percolating through the soil and transitioning into groundwater, nutrients transferred into the groundwater system would have been deposited prior to the two-week experiment. Therefore, the presence of sheep in the paddock was unlikely to have influenced water quality, as there was no difference in total nitrogen loads between treatments. The results of current study suggest that the majority of N detected in the stream was either transported as dissolved organic or particulate nitrogen labile nitrogen already present in the soil system.

In hill country, soil erosion tends to be elevated (McDowell et al., 2004), resulting in particulate loss of P being the dominant form of loss (Hart et al., 2004). During the summer study, total phosphorus concentrations (TPC) and total phosphorus load (TPL) were not influenced by trough access treatment however were higher on D7 compared to D6. In autumn, TPC and TPL were not influenced by either treatment or sampling day. In both seasons TPC and TPL were higher at the inflow than outflow sampling sites. In summer, the peak TP concentration was recorded following a rainfall event, however, in autumn there appeared to be no relationship with rainfall events. Cournane et al. (2011) reported that there was a seasonal effect on P whereby the greatest P loads occurred in winter and the greatest P concentrations in drier summer months. They also reported that rainfall had a significant effect on TPL but not TPC. They found that during periods when sheep were grazing paddocks TP concentrations in surface runoff water was 0.435mg/l and suspended sediment was 0.283g/l. During irregular rainfall events in summer months, which produced runoff, P concentrations may be enriched as a result of low volumes of, and the greater incidence of, available P from dung deposits. In these conditions high P concentrations may be more detrimental to surface water bodies due to the greater potential for algal growth (i.e. increased light and temperature) (Cournane et al., 2011).

In both the summer and autumn studies there was no difference in sediment load or concentration between the inflow and outflow sampling locations. This suggests that the rate of sediment that was introduced to the stream from the study site was equal to the amount of sediment deposited along the section of stream in the study site. During the summer study, sediment load and concentration was higher on D7 compared to D6 following the rain event. D7 corresponded with the period of water trough access and as a result, there was a significant difference in SS loads between treatment periods. During the autumn study, both sediment load and concentration were higher during the period with restricted trough access than when access was unrestricted. The increase in sediment measured in the stream was possibly linked to the increase in the duration that sheep were in proximity of some areas of the stream zone. Sediment mobilised from reaches upstream of the paddock, however, can also explain in part some of these results this as there was no difference between sampling sites indicating that there were minimal sediment inputs into the stream throughout the trial area. Rainfall can also increase SS through dislodging and mobilising particles across an area as it travels into the stream. Rainfall during both experiments probably contributed to the SSL measured. Suspended sediment loads have been reported to increase with increasing slope, but decrease exponentially as herbage mass increases (Burkitt et al., 2017). Soil disturbance and erosion are associated with stream disturbances, such as local stock crossings, stream bank erosion and point source discharges (Buck et al., 2004). Due to the behaviour of the sheep observed in this study, stream bank damage resulting in sediment particles entering the waterway was likely to be insignificant.

The potential for sheep to impact on water quality increases as sheep spend more time in the riparian zone. In the summer and autumn studies, *E. coli* concentrations and loads were higher at the outflow than inflow measurment sites suggesting that the study site was the source of *E. coli* entering the stream. On D7 of the summer study, *E. coli* concentrations were observed to increase 4-fold compared with the previous day and was probabaly linked to rainfall events. As a result of this increase in *E. coli*, the unrestricted trough treatment had higher *E. Coli* loads than the restricted trough treatment. In the autumn study, *E. Coli* concentrations and loads did not differ between sampling day or treatment. In New Zealand, where fresh water bodies are used for recreation there is a high correlation between

E. coli in the range of 200-500 *E. coli* MPN/100 ml^{-1} and the incidence of disease (Donnison et al., 2004). *E. coli* concentrations follow an annual pattern with the highest concentrations recorded in summer (December) and autumn (May) and the lowest in late winter (August) and spring (October) (Donnison et al., 2004). Contamination of water with livestock excrement can occur through a variety of pathways and presents a potential health risk to human and animals (Zahedi et al., 2020). The deposition of faeces near a waterway may, on occasion, be nearly as damaging as direct deposition into water due to the high potential for wash-in by surface runoff and entrainment by rising water levels (Collins et al., 2007). Water moves over the land, entraining *E. Coli* in sheep faeces and historical biological matter is transported in suspension into waterways (Dymond et al., 2016). Faecal deposition on hill slopes (which occupy the greatest area of hill country paddocks) provide only a small proportion of nutrient requirements of pasture. The proportion of faeces deposited across a paddock decreases sharply with increasing steepness of the slope (Rowarth et al., 1985). Depending on the quantity of excreta within a paddock and the survivability of the bacteria, historic excrement can also be a problem. This effect is prevalent when the soil infiltration capacity is exceeded by rainfall following dry periods as found in the summer study in this thesis. It is difficult for farmers to prevent sheep from depositing faeces near waterways, but conservative management of a paddock can reduce the build-up of excreta. Ensuring reasonable intervals between grazing events can allow the microbes within a soil to break down the excreta.

4.1 Limitations

The findings of these two experiments have enhanced our understanding of the interactions of sheep with a natural waterway and resulted in some recommendations for reducing the impact of sheep. As this study was conducted in the Manawatu region of New Zealand, with Romney sheep, any inferences made cannot necessarily be extrapolated against other hill country environments with different topographical features, streams of different orders or different sheep breeds. This research however is indicative of the influences of sheep behaviour around a natural waterway. The lack of replication of these experiments was a major limitation as the differences observed between treatments could be attributed to a number of environmental factors as well as the presence of sheep.

One limitation experienced in the summer study was the battery life of accelerometers was insufficient to generate a complete data set. In the summer study, accelerometer data was recorded for 8 of the 14 study days which prevented the comparison of the effect of treatment on the time ewes spent in proximity of the camera locations. This impact was minimised by the video footage which enabled comparison of the duration that sheep spent in proximity to each camera. This issue was fixed in the autumn study by delaying the initiation of the devices until the evening before the data collection was begun.

Sheep behaviour analysis from video footage was limited by the type of the cameras used. As the cameras were motion activated, it was not possible to know if every occasion sheep were within range of the cameras was captured. Due to this uncertainty, it was not possible to calculate the percentage of time sheep performed each behaviour in the stream zone over the experiment. Furthermore, it was not possible to determine how much time sheep spent in the stream zone relative to the rest of the paddock.

In each study GPS units were randomly allocated to 20 sheep for three days of each seven-day treatment. This allocation of GPS units limited the understanding individual sheep mobility. In these experiments GPS locations recorded in the stream zone were a small subset of the total data collected. Video surveillance footage, however, suggested there was a strong individual sheep preference for the stream zone. More GPS units may have provided a better representation of how the sheep moved around the stream zone. In particular, the GPS locations of sheep that exhibited a higher frequency of behavioural events in the stream zone could have been further investigated. GPS data was limited by the accuracy of the units which was 1.4m. Improved accuracy would have provided a more precise picture of sheep movement and location within the stream zone.

Pasture quantity and quality are important factors that influence sheep behaviour. Pasture mass was recorded three times and moisture four times during each experiment. More samples, potentially every second day and at a range of locations would have yielded a better understanding of the role pasture production and composition have on sheep location preference. Hyperspectral sensing using ground-based equipment has been demonstrated to be successful in determining pasture nutrient content (N, P, K, S) and parameters such as dry matter content and metabolizable energy (Yule et al., 2015). Utilising this technology could have created a better picture of pasture within the stream zone, slopes and flat areas of the paddock which could improve the management recommendations for these areas.

4.2 Further Research Opportunities

It has been well established that lambs learn from their mother (Saint-Dizier et al., 2007) and information can be easily passed from experienced too inexperienced animals as a result of social facilitation (Launchbaugh et al., 2001; Thorhallsdottir et al., 1990). If a sheep can learn and exhibit preference for certain foods, they may also learn to interact or avoid waterways. There also may be a genetic component to the preference that some sheep appear to show for waterways. Whether the preference for interacting with waterways it is taught or inherited, there is a possibility of changing the preference of individuals prior to exposure to the stimuli. As noted in the current studies, preference for interacting with the waterway was limited to a small number of sheep. Therefore, the management of these animals that showed a preference would be increased in comparison to the rest of the mob that didn't show an affinity for the stream. There may be potential to use audio cues to train animals to avoid a specified area. Similarly, lambing ewes could be placed in paddocks that did not have a free-flowing stream so that lambs would not be exposed to waterways post birth.

A range of chemical and phytotoxin deterrents could be used to train sheep not to drink water from streams. Many plant toxins have a bitter taste (e.g., saponins and cyanogenic glycosides), offensive odour (e.g., terpenes), or provoke an astringent sensation when eaten (e.g., tannins) (Launchbaugh et al., 2001). Herbivores learn to prefer specific flavour intensities if they consistently signal higher nutrient or lower toxin concentrations (Villalba & Provenza, 2000). Therefore, odours could be used to train livestock to avoid a plant with such "olfactory aposematism" serving as a primary warning system signalling the potentially deleterious effects of toxic plants (Provenza et al., 2000). Further, through the inclusion of unpalatable or phytotoxic species within the riparian zone, sheep could be trained to avoid entering this area. Planting the bank close to the stream with an unpalatable forage may be enough to deter the sheep from entering this area. This would then decrease the costs associated with implementing a blanket fencing policy for waterway management.

Further research examining other soil types, stocking rates and pasture covers would be beneficial in developing the research base. Experiments could involve creating management zones within hill country paddocks transected by a stream based on soil type, pasture composition and density and topography. Each zone could be individually tested to determine sheep behaviour and water quality characteristics. This would enable a more detailed description of the behaviour of sheep in response to a specific range of environments and the risk of nutrient loss. From this, management decisions could be based on specific areas that are at higher risk for a degradation in environmental quality. This research could be further expanded by populating each zone with a diverse plant community to improve nutrient adsorption or fenced to protect soil stability and prevent erosion. Managing these areas could also involve targeted fencing of identified critical source areas, improving soil health by introducing plant diversity or retiring areas into native bush.

Understanding trough placement within a paddock could generate further information on the effects of topography and slope on sheep drinking behaviours. This could lead to improved management of a paddock through enhanced utilisation of the areas around a trough. Sheep farmers can enhance water conservation through the investment in abstraction of ground water resources, rainwater and runoff harvesting infrastructure, and evaporation mitigation technologies (Chikwanha et al., 2021). The water available as underground sources can be implemented for potable provision of freshwater for sheep and can be combined with solar or wind water pumps to provide a cheaper energy source for sustainable ground water extraction. Livestock water supplies powered by solar-powered (photovoltaic) systems have a high investment cost, produce no carbon emissions, generate no noise, and have low operational and maintenance costs (Aliyu et al., 2018)

4.3 Implications and Recommendations

The benefits of this research are targeted at the guardians of our land, our farmers and the respective policy makers influencing their ability to farm. From this research, it appears that sheep accessing a stream during summer and autumn had a negligible effect on total nitrogen, nitrate-N, ammonium, total phosphorus and suspended sediment concentration and loads. These studies showed that sheep had minimal interaction with the natural stream even when access to a water trough removed. In these studies sheep appeared to have minimal impact on water quality and are likely to pose a negligible risk to water quality in hill country streams. The primary influence on water quality was rainfall events, which a farmer cannot control. Including sheep in the exclusion policy (Resource Management Act, 2020) would likely inhibit the productivity of sheep farming for New Zealand’s economy.

Mitigating the influence that sheep farming has on water quality by improving the management of a hill country paddock will aid in the regeneration of the farming ecosystem. Effective land management strategies to control nutrient loss in steep catchments would involve focus on mitigating sediment transport (Buck et al., 2004) and erosion potential. The critical observation by a farmer compared to a policy writing bureaucrat, who understands the niche farming operation they operate in, is better suited to manage the natural resources of the land. Active management of the physical resources through increasing grazing residuals, decreasing stocking rates, promoting microbial and plant diversity could reduce the impact sheep farming has the New Zealand hill country environment. Identifying areas that are erosion prone, at a high risk of nutrient loss or that contain bare ground will enable the farmer to adjust their management of these areas, by limiting stock access points to reduce damage. Planting cover crops, trees or native fauna, or retiring the land from grazing could also be used to reduce the impact of sheep on higher order streams in hill country areas. Reducing artificial inputs and aligning nutrient availability with plant demand and animal requirements reduces nutrient loss and decreases the risk hill country sheep farming has on water quality.

4.4 Conclusion

Throughout the two experiments, certain limitations of technological equipment created problems with generating a complete data set. However, accounting for the battery constraints and laboratory difficulties, a relative understanding of the impact sheep have on water quality in New Zealand was created. I hope that these results can be extrapolated into a wide range of ecological systems to further our understanding of sheep within the farmed environment and aid in further management and policy decisions.

Negative water quality impacts were primarily observed following a rainfall event during both seasonal trials which may in part be related to the presence of grazing sheep but may also be linked to the wider nutrient movement patterns within the farmed landscape. Rain resulted in an increase in water flow rate of the stream. As a consequence, concentrations of *E. coli*, TN, TP, and SS measured in the water samples at both the inflow and outflow sampling locations were generally elevated. During the summer trial during the rainfall event on D7, the median *E. coli* concentration recorded was 4350 cfu/100ml. This value exceeds the freshwater recreation microbial assessment category water quality guideline D grade threshold of >550 MPN/100ml. Given that autumn is typically cooler, and five rainfall events occurred during this study, the survival and transport of *E coli* from fresh and aged sheep faeces to the stream was likely to have led to the measured deterioration in water quality. Managing a paddock to mitigate the transport of excrement will reduce the impact on water quality. Shorter grazing rotations that result in longer pasture residuals will reduce the risk. It is important to note that during both experiments, no sheep were observed to defecate directly into the stream. From these results, it is clear that the measured degradation in water quality was primarily linked to rainfall events rather than from the direct presence of sheep within the paddock or from their unrestricted access to the stream zone.

During both experiments, individual sheep were highlighted as exhibiting most of the behaviours within the stream zone. Furthermore, this suggests that access to a reticulated water system within a paddock may not necessarily result in sheep drinking from it nor did its presence alter sheep behaviour or interaction with the stream. The trial also showed that the sheep spent proportionately less time in the stream zone relative to the rest of the paddock and the sheep that did enter the stream zone did so to mainly graze. The results from both experiments indicated that the moisture in pasture was in part, sufficient enough to maintain the water requirements of the grazing sheep. Access to a water trough did not influence the frequency or duration of drinking events by sheep from the stream during either experiment.

Within the summer and autumn experiments, a key finding was the influence of slope on sheep behaviour. The slope surrounding the stream at certain areas along the stream bed (>20°) was not usually accessed by the sheep. This was probably linked to the flat areas of the paddock having more forage available. However, as this forage began to decrease throughout the duration of the trial, sheep began to explore the steeper regions. This is a potential problem based on the erosion susceptibility of stepper regions and the increased likelihood of nutrients in effluent being mobilised by overland flow during rainfall events.

Sheep play a critical role in the management of our hill country through maintaining the biodiversity of our hill country and recycling nutrients (Maseyk et al., 2021). The importance of sheep farming extends into the whakapapa of our nation. Sheep agroecosystems generate employment, strengthen identities, and maintain cultural landscapes (O'Flanagan et al., 2011). In a world depraved of an adequate food supply, we would progress our nation further through improving our farmers ability to farm, rather than condemn them with sanctions.

References

Aarons, & Gourley. (2013). The role of riparian buffer management in reducing off-site impacts from grazed dairy systems. *Renewable Agriculture and Food Systems, 28*(1), 1-16.

Aganga. (1992). Water utilization by sheep and goats in northern Nigeria. *World Animal Review, 73*.

Agouridis, Workman, Warner, & Jennings. (2005). Livestock grazing management impacts on stream water quality: a review. *Journal of the American Water Resources Association, 41*(3), 591-606.

Aguilar, Collins, Dunston-Clarke, Wickham, Fleming, & Barnes. (2020). Impact of shearing sheep on feeding and behaviour during the pre-embarkment feedlot phase of live export. *Animal Production Science, 60*(7), 936-943.

Aguilar, Herrero, & Polo. (2010). Topographic effects on solar radiation distribution in mountainous watersheds and their influence on reference evapotranspiration estimates at watershed scale. *Hydrology and Earth System Sciences, 14*(12), 2479-2494.

Aislabie, McLeod, Ryburn, McGill, & Thornburrow. (2011). Soil type influences the leaching of microbial indicators under natural rainfall following application of dairy shed effluent. *Soil Research, 49*(3), 270-279.

Akinmoladun, Muchenje, Fon, & Mpendulo. (2019). Small ruminants: farmers' hope in a world threatened by water scarcity. *Animals, 9*(7), 456.

Al-Ramamneh, Riek, & Gerken. (2010). Deuterium oxide dilution accurately predicts water intake in sheep and goats. *Animal, 4*(9), 1606-1612.

Al-Ramamneh, Riek, & Gerken. (2012). Effect of water restriction on drinking behaviour and water intake in German black-head mutton sheep and Boer goats. *Animal, 6*(1), 173-178.

Alegbeleye, & Sant'Ana. (2020). Manure-borne pathogens as an important source of water contamination: An update on the dynamics of pathogen survival/transport as well as practical risk mitigation strategies. *International journal of hygiene and environmental health, 227*, 113524.

Aliyu, Hassan, Said, Siddiqui, Alawami, & Elamin. (2018). A review of solar-powered water pumping systems. *Renewable and Sustainable Energy Reviews, 87*, 61-76.

Alqaisi, Al-Jazmi, Al-Abri, Al Kalaldeh, Al-Sabahi, & Al-Marzooqi. (2020). Effect of diet quality and shearing on feed and water intake, in vitro ruminal methane production, and blood parameters of Omani sheep. *Tropical animal health and production, 52*(3), 1115-1124.

Alvarenga, Borges, Palkovič, Rodina, Oddy, & Dobos. (2016). Using a three-axis accelerometer to identify and classify sheep behaviour at pasture. *Applied Animal Behaviour Science, 181*, 91-99.

Arnold, & Pahl. (1974). Some aspects of social behaviour in domestic sheep. *Animal Behaviour, 22*(3), 592-600.

Ashworth, & Ferguson. (1986). Interrelationships of channel processes, changes and sediments in a proglacial braided river. *Geografiska Annaler: Series A, Physical Geography, 68*(4), 361-371.

Australian Government (2021). *Australian and New Zealand Guidelines for Marine and Freshwater Quality - https://www.waterquality.gov.au/anz-guidelines/your-location/new-zealand*

Bagshaw. (2002). *Factors influencing direct deposition of cattle faecal material in riparian zones*. Ministry of Agriculture and Forestry Wellington.

Bailey, & Brown. (2011). Rotational grazing systems and livestock grazing behavior in shrub-dominated semi-arid and arid rangelands. *Rangeland Ecology & Management, 64*(1), 1-9.

Bailey, Gross, Laca, Rittenhouse, Coughenour, Swift, & Sims. (1996). Mechanisms that result in large herbivore grazing distribution patterns. *Rangeland Ecology & Management/Journal of Range Management Archives, 49*(5), 386-400.

Bargh. (1977). Output of water, suspended sediment and phosphorus and nitrogen forms from a small forested catchment. *New Zealand journal of forestry science, 7*(2), 162-171.

Barros de Freitas, Bartholazzi Junior, Quirino, & Costa. (2021). Water and food utilization efficiencies in sheep and their relationship with some production traits. *Small Ruminant Research, 197*.

Barwick, Lamb, Dobos, Welch, & Trotter. (2018). Categorising sheep activity using a tri-axial accelerometer. *Computers and electronics in agriculture, 145*, 289-297.

Baumont, Cohen-Salmon, Prache, & Sauvant. (2004). A mechanistic model of intake and grazing behaviour in sheep integrating sward architecture and animal decisions. *Animal Feed Science and Technology, 112*(1-4), 5-28.

Beatty, Barnes, Fleming, Taylor, & Maloney. (2008). The effect of fleece on core and rumen temperature in sheep. *Journal of Thermal Biology, 33*(8), 437-443.

Beede. (2012). What will our ruminants drink? *Animal Frontiers, 2*(2), 36-43.

Beef and Lamb. (2020a). *Compendium of New Zealand Farm Facts*.

Beef and Lamb. (2020b). *Hill country sheep and beef farms fact sheet*. https://beeflambnz.com/knowledge-hub/PDF/hill-country-sheep-and-beef-farms.pdf

Belčáková, Vojtkova, Pauková, & Offertalerova. (2019). The impact of floodplain vegetation on the erosion-sedimentation processes in fluvisols during flood events. *Applied Ecology and Environmental Research, 17*(3).

Bensemann, & Shadbolt. (2015). Farmers' choice of marketing strategy: A study of New Zealand lamb producers. *International Food and Agribusiness Management Review, 18*, 211-243.

Betteridge, Costall, Balladur, Upsdell, & Umemura. (2010). Urine distribution and grazing behaviour of female sheep and cattle grazing a steep New Zealand hill pasture. *Animal Production Science, 50*(6), 624-629.

Betteridge, Hoogendoorn, Griffiths, Costall, Carter, & Laube. (2020). Monitoring urine distribution by grazing livestock. XXI International Grassland Congress Proceedings/VIII International Rangeland Congress Hohhot, China.

Betteridge, Kawamura, Costall, Ganesh, Luo, Koolaard, & Yoshitoshi. (2017). Intensive Livestock Farming on New Zealand Hill Country Farms Creates Critical Source Areas of Potential Pollution. *Journal of Integrated Field Science, 14*, 103.

Bilotta, Brazier, & Haygarth. (2007). The impacts of grazing animals on the quality of soils, vegetation, and surface waters in intensively managed grasslands. *Advances in agronomy, 94*, 237-280.

Blankenberg, & Skarbøvik. (2020). Phosphorus retention, erosion protection and farmers' perceptions of riparian buffer zones with grass and natural vegetation: Case studies from South-Eastern Norway. *AMBIO - A Journal of the Human Environment, 49*(11), 1838-1849.

Boissy, Manteuffel, Jensen, Moe, Spruijt, Keeling, Winckler, Forkman, Dimitrov, & Langbein. (2007). Assessment of positive emotions in animals to improve their welfare. *Physiology & Behavior, 92*(3), 375-397.

Booker. (2018). Quantifying the hydrological effect of permitted water abstractions across spatial scales. *Environmental Management, 62*(2), 334-351.

Bradford, Morales, Zhang, Harvey, Packman, Mohanram, & Welty. (2013). Transport and fate of microbial pathogens in agricultural settings. *Critical Reviews in Environmental Science and Technology, 43*(8), 775-893.

Brennan, Johnson, & Olson. (2021). Classifying season long livestock grazing behavior with the use of a low-cost GPS and accelerometer. *Computers and electronics in agriculture, 181*, 105957.

Bristow, Whitehead, & Cockburn. (1992). Nitrogenous constituents in the urine of cattle, sheep and goats. *Journal of the Science of Food and Agriculture, 59*(3), 387-394.

Bronstert, & Plate. (1997). Modelling of runoff generation and soil moisture dynamics for hillslopes and micro-catchments. *Journal of Hydrology, 198*(1-4), 177-195.

Brown, Kays, Wikelski, Wilson, & Klimley. (2013). Observing the unwatchable through acceleration logging of animal behavior. *Animal Biotelemetry, 1*(1), 1-16.

Bryan, & Kandulu. (2011). Designing a policy mix and sequence for mitigating agricultural non-point source pollution in a water supply catchment. *Water resources management, 25*(3), 875-892.

Buck, Niyogi, & Townsend. (2004). Scale-dependence of land use effects on water quality of streams in agricultural catchments. *Environmental pollution, 130*(2), 287-299.

Buda, Kleinman, Srinivasan, Bryant, & Feyereisen. (2009). Factors influencing surface runoff generation from two agricultural hillslopes in central Pennsylvania. *Hydrological Processes: An International Journal, 23*(9), 1295-1312.

Burkitt, Winters, & Horne. (2017). Sediment and nutrient losses under winter cropping on two Manawatu hill country soils. *Journal of New Zealand Grasslands*, 27-33.

Burns, & Nguyen. (2002). Nitrate movement and removal along a shallow groundwater flow path in a riparian wetland within a sheep-grazed pastoral catchment: Results of a tracer study. *NEW ZEALAND JOURNAL OF MARINE AND FRESHWATER RESEARCH, 36*(2), 371-385.

Burt, Matchett, Goulding, Webster, & Haycock. (1999). Denitrification in riparian buffer zones: the role of floodplain hydrology. *Hydrological processes, 13*(10), 1451-1463.

Butler, Ranells, Franklin, Poore, & Green Jr. (2008). Runoff water quality from manured riparian grasslands with contrasting drainage and simulated grazing pressure. *Agriculture, Ecosystems & Environment, 126*(3-4), 250-260.

Caloiero. (2015). Analysis of rainfall trend in New Zealand. *Environmental Earth Sciences, 73*(10), 6297-6310.

Casamassima, Palazzo, Nardoia, D'Alessandro, & Vizzarri. (2018). Effect of water restriction on milk yield and quality in Lacaune breed ewes. *Journal of animal physiology and animal nutrition, 102*(2), 677-685.

Causley. (1990). Effect of minimum tillage, sowing rate, and sowing time on the yield of a sorghum-sudangrass hybrid in the Manawatu, New Zealand. *New Zealand Journal of Agricultural Research, 33*(1), 15-20.

Champion, Rutter, Penning, & Rook. (1994). Temporal variation in grazing behaviour of sheep and the reliability of sampling periods. *Applied Animal Behaviour Science, 42*(2), 99-108.

Champion, & Tanner. (2000). Seasonality of macrophytes and interaction with flow in a New Zealand lowland stream. *Hydrobiologia, 441*(1), 1-12.

Chapman, Parsons, Cosgrove, Barker, Marotti, Venning, Rutter, Hill, & Thompson. (2007). Impacts of spatial patterns in pasture on animal grazing behavior, intake, and performance. *Crop Science, 47*(1), 399-415.

Chedid, Jaber, Giger-Reverdin, Duvaux-Ponter, & Hamadeh. (2014). Water stress in sheep raised under arid conditions. *Canadian Journal of Animal Science, 94*(2), 243-257.

Cheng, Nicol, Dewhurst, & Edwards. (2013). The effects of dietary nitrogen to water-soluble carbohydrate ratio on isotopic fractionation and partitioning of nitrogen in non-lactating sheep. *Animal, 7*(8), 1274-1279.

Chibuike, Burkitt, Bretherton, Singh, & Bishop. (2021). Dissolved Organic Carbon Concentration and Denitrification Capacity of a New Zealand Hill Country Soil After Forage Crop Establishment. *Earth Systems and Environment, 5*(2), 419-432.

Chikwanha, Mupfiga, Olagbegi, Katiyatiya, Molotsi, Abiodun, Dzama, & Mapiye. (2021). Impact of water scarcity on dryland sheep meat production and quality: Key recovery and resilience strategies. *Journal of Arid Environments, 190*, 104511.

Choudhary, Akramkhanov, & Saggar. (2002). Nitrous oxide emissions from a New Zealand cropped soil: tillage effects, spatial and seasonal variability. *Agriculture, Ecosystems & Environment, 93*(1-3), 33-43.

Cockram. (2004). A review of behavioural and physiological responses of sheep to stressors to identify potential behavioural signs of distress. *Animal Welfare, 13*(3), 283-291.

Collins, Elliott, & Adams. (2005). Overland flow delivery of faecal bacteria to a headwater pastoral stream. *Journal of applied microbiology, 99*(1), 126-132.

Collins, McLeod, Hedley, Donnison, Close, Hanly, Horne, Ross, Davies-Colley, Bagshaw, & Matthews. (2007). Best management practices to mitigate faecal contamination by livestock of New Zealand waters. *New Zealand Journal of Agricultural Research, 50*(2), 267-278.

Collins, & Rutherford. (2004). Modelling bacterial water quality in streams draining pastoral land. *Water Research, 38*(3), 700-712.

Coorporation. (2018). https://office.microsoft.com/excel

Cordova-Torres, Costa, Medeiros, ARAÚJO, Ramos, & Alves. (2017). Performance of sheep fed forage cactus with total water restriction. *Revista Brasileira de Saúde e Produção Animal, 18*, 369-377.

Cournane, McDowell, Littlejohn, & Condron. (2011). Effects of cattle, sheep and deer grazing on soil physical quality and losses of phosphorus and suspended sediment losses in surface runoff. *Agriculture, Ecosystems & Environment, 140*(1-2), 264-272.

Daigneault, Eppink, & Lee. (2017). A national riparian restoration programme in New Zealand: Is it value for money? *Journal of environmental management, 187*, 166-177.

Das, Maitra, & Bisht. (1999). Genetic and non-genetic factors influencing ingestive behavior of sheep under stall-feeding conditions. *Small Ruminant Research, 32*(2), 129-136.

Davies-Colley. (2013). River water quality in New Zealand: an introduction and overview. *Ecosystem services in New Zealand: conditions and trends. Manaaki Whenua Press, Lincoln*, 432-447.

Davies-Colley, & Hughes. (2020). Sediment-related water quality of small hill-country streams near Whatawhata, New Zealand. Response to integrated catchment management (ICM). *NEW ZEALAND JOURNAL OF MARINE AND FRESHWATER RESEARCH, 54*(3), 329-353.

Davies-Colley, Valois, & Milne. (2018). Faecal contamination and visual clarity in New Zealand rivers: correlation of key variables affecting swimming suitability. *Journal of Water and Health, 16*(3), 329-339.

Davis. (2014). Nitrogen leaching losses from forests in New Zealand. *New Zealand journal of forestry science, 44*(1), 1-14.

Davis Instruments. (2014). Vantage Pro 2 User Manual. https://cdn.shopify.com/s/files/1/0515/5992/3873/files/07395-234_im_06312.pdf?v=1623784828

Death, Canning, Magierowski, & Tonkin. (2018). Why aren't we managing water quality to protect ecological health. *Farm Environmental Planning—Science, Policy and Practice. Massey University, New Zealand: Occasional Report, 31*.

Decandia, Giovanetti, Molle, Acciaro, Mameli, Cabiddu, Cossu, Serra, Manca, & Rassu. (2018). The effect of different time epoch settings on the classification of sheep behaviour using tri-axial accelerometry. *Computers and electronics in agriculture, 154*, 112-119.

Dinnes, Karlen, Jaynes, Kaspar, Hatfield, Colvin, & Cambardella. (2002). Review and interpretation: Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils.

Dodd, Barker, & Wedderburn. (2004). Plant diversity effects on herbage production and compositional changes in New Zealand hill country pastures. *Grass and Forage Science, 59*(1), 29-40.

Dodd, & Sheath. (2003). Persistence: the key to legume performance in summer-dry hill country. *NZGA: Research and Practice Series, 11*, 73-79.

Dodd, Tozer, Vogeler, Greenfield, Stevens, Rhodes, & Quilter. (2020). Quantifying the value proposition for white clover persistence on a New Zealand summer-dry hill-country farm. *Journal of New Zealand Grasslands*, 199-209.

Doehring, Young, & Robb. (2020). Demonstrating efficacy of rural land management actions to improve water quality-How can we quantify what actions have been done? *Journal of environmental management, 270*, 110475.

Donnison, Ross, & Thorrold. (2004). Impact of land use on the faecal microbial quality of hill-country streams. *NEW ZEALAND JOURNAL OF MARINE AND FRESHWATER RESEARCH*, *38*(5), 845-855.

Dorner, Anderson, Slawson, Kouwen, & Huck. (2006). Hydrologic modeling of pathogen fate and transport. *Environmental Science & Technology, 40*(15), 4746-4753.

Dougherty, Fleming, Cox, & Chittleborough. (2004). Phosphorus transfer in surface runoff from intensive pasture systems at various scales: A review. *Journal of Environmental Quality*, *33*(6), 1973-1988.

Dove, Freer, & Foot. (2000). The nutrition of grazing ewes during pregnancy and lactation: a comparison of alkane-based and chromium/in vitro-based estimates of herbage intake. *Australian Journal of Agricultural Research*, *51*(6), 765-777.

Dumont, & Boissy. (2000). Grazing behaviour of sheep in a situation of conflict between feeding and social motivations. *Behavioural Processes*, *49*(3), 131-138.

Dumont, & Petit. (1998). Spatial memory of sheep at pasture. *Applied Animal Behaviour Science, 60*(1), 43-53.

Dumont, Prache, Carrère, & Boissy. (2007). How do sheep exploit pastures? An overview of their grazing behaviour from homogeneous swards to complex grasslands. *Options Méditerranéennes, Series A*, *74*, 317-328.

Dwyer. (2008). Environment and the sheep. In *The Welfare of Sheep* (pp. 41-79).

Dymond, Serezat, Ausseil, & Muirhead. (2016). Mapping of Escherichia coli sources connected to waterways in the Ruamahanga catchment, New Zealand. *Environmental Science & Technology, 50*(4), 1897-1905.

Elwan, Singh, Patterson, Roygard, Horne, Clothier, & Jones. (2018). Influence of sampling frequency and load calculation methods on quantification of annual river nutrient and suspended solids loads. *Environmental monitoring and assessment, 190*(2), 1-18.

Espanto. (2015). *Assessment of the transport and transformation of nitrogen in the unsaturated and saturated zones under two dairy farms in the Manawatu River catchment : a thesis presented in partial fulfilment of the requirements for the degree of Master in Environmental Management at the Institute of Agriculture and Environment, Massey University, Palmerston North, Manawatu, New Zealand* [Masters, Massey University]. http://hdl.handle.net/10179/8322

Esri. (2021). *ArcGIS Pro 2.8.1*. www.arcgis.com

Fensham, & Fairfax. (2008). Water-remoteness for grazing relief in Australian arid-lands. *Biological Conservation*, *141*(6), 1447-1460.

Fernandez. (2017). Adoption of erosion management practices in New Zealand. *Land Use Policy, 63*, 236-245.

Filipčík, Hanzlikova, Kuchtik, Reckova, Hosek, Pesan, & Kopec. (2020). Assessment of some behavioral patterns of a sheep flock on pasture. *Animal Welfare, Etológia és Tartástechnológia, 16*(1), 8-14.

Fogarty, Swain, Cronin, & Trotter. (2018). Autonomous on-animal sensors in sheep research: A systematic review. *Computers and electronics in agriculture, 150*, 245-256.

Fonte, Vanek, Oyarzun, Parsa, Quintero, Rao, & Lavelle. (2012). Pathways to agroecological intensification of soil fertility management by smallholder farmers in the Andean highlands. *Advances in agronomy, 116*, 125-184.

Forbes. (1968). The water intake of ewes. *British Journal of Nutrition, 22*(1), 33-43.

Forbes, & Hodgson. (1985). The reaction of grazing sheep and cattle to the presence of dung from the same or the other species. *Grass and Forage Science, 40*(2), 177-182.

Fox, Heeren, Miller, Mittelstet, & Storm. (2011). Flow and transport experiments for a streambank seep originating from a preferential flow pathway. *Journal of Hydrology, 403*(3-4), 360-366.

Fox, & Wilson. (2010). The role of subsurface flow in hillslope and stream bank erosion: a review. *Soil Science Society of America Journal, 74*(3), 717-733.

Freeze. (1974). Streamflow generation. *Reviews of Geophysics, 12*(4), 627-647.

Friard, & Gamba. (2016). BORIS: a free, versatile open-source event-logging software for video/audio coding and live observations. *Methods in ecology and evolution, 7*(11), 1325-1330.

Gall, Swales, Davies-Colley, & Bremner. (2019). Predicting visual clarity and light penetration from water quality measures in New Zealand estuaries. *Estuarine, Coastal and Shelf Science, 219*, 429-443.

Garry, McGovern, Boland, Rinne, Kuoppala, Baumont, Lewis, & O'Donovan. (2021). How does herbage mass effect voluntary dry matter intake and in vivo organic matter digestibility in sheep and the in vitro gas production of perennial ryegrass? *Livestock Science, 244*, 104345.

Gaur, Chand, Louhaichiz, Johnson, Mishra, & Roy. (2013). Role of GPS in monitoring livestock migration. *Journal of Indian Cartographer, 33*, 496-501.

Gillingham, & Thorrold. (2000). A review of New Zealand research measuring phosphorus in runoff from pasture. *Journal of Environmental Quality, 29*(1), 88-96.

Giovanetti, Decandia, Molle, Acciaro, Mameli, Cabiddu, Cossu, Serra, Manca, & Rassu. (2017). Automatic classification system for grazing, ruminating and resting behaviour of dairy sheep using a tri-axial accelerometer. *Livestock Science, 196*, 42-48.

Goddard, Waterhouse, Dwyer, & Stott. (2006). The perception of the welfare of sheep in extensive systems. *Small Ruminant Research, 62*(3), 215-225.

Goeller, Burbery, Febria, Collins, Burrows, Simon, Harding, & McIntosh. (2019). Capacity for bioreactors and riparian rehabilitation to enhance nitrate attenuation in agricultural streams. *Ecological Engineering, 134*, 65-77.

Gonyou. (1984). The role of behavior in sheep production: a review of research. *Applied Animal Ethology, 11*(4), 341-358.

Gougoulis, Kyriazakis, & Fthenakis. (2010). Diagnostic significance of behaviour changes of sheep: A selected review. *Small Ruminant Research, 92*(1-3), 52-56.

Goulsbra, Evans, & Lindsay. (2014). Temporary streams in a peatland catchment: pattern, timing, and controls on stream network expansion and contraction. *Earth Surface Processes and Landforms, 39*(6), 790-803.

Grassia. (1978). A technique in the study of aggregative behaviour of sheep. *Applied Animal Ethology, 4*(4), 369-377.

Greenwood, & Zhang. (2020). Comparing grain size composition of inter-rill and rill-eroded sediment from cultivated hillslope soils using caesium-134 and cobalt-60 as tracers. *Soil and Tillage Research, 198*, 104532.

Guevara-Escobar, Kemp, Mackay, & Hodgson. (2007). Pasture production and composition under poplar in a hill environment in New Zealand. *Agroforestry Systems, 69*(3), 199-213.

Guo, Ryan, Feng, & Xiao. (2022). Association of Common Zoonotic Pathogens With Concentrated Animal Feeding Operations. *Frontiers in microbiology*, 4225.

Hall, Schmidt, & Broom. (1997). Feeding behaviour and the intake of food and water by sheep after a period of deprivation lasting 14 h. *Animal Science, 64*(1), 105-110.

Hallama, Pekrun, Lambers, & Kandeler. (2019). Hidden miners–the roles of cover crops and soil microorganisms in phosphorus cycling through agroecosystems. *Plant and Soil, 434*(1), 7-45.

Harding. (2004). *Freshwaters of New Zealand*. New Zealand Hydrological Society.

Harrison, McAree, Mulville, & Sullivan. (2019). The problem of agricultural 'diffuse'pollution: Getting to the point. *Science of the total environment, 677*, 700-717.

Hart, Quin, & Nguyen. (2004). Phosphorus runoff from agricultural land and direct fertilizer effects: A review. *Journal of Environmental Quality, 33*(6), 1954-1972.

Hauer, Locke, Dreitz, Hebblewhite, Lowe, Muhlfeld, Nelson, Proctor, & Rood. (2016). Gravel-bed river floodplains are the ecological nexus of glaciated mountain landscapes. *Science Advances, 2*(6), e1600026.

Hefting, Bobbink, & de Caluwe. (2003). Nitrous oxide emission and denitrification in chronically nitrate-loaded riparian buffer zones. *Journal of Environmental Quality, 32*(4), 1194-1203.

Heitschmidt, & Stuth. (1991). *Grazing management: an ecological perspective*.

Herlin, Brunberg, Hultgren, Högberg, Rydberg, & Skarin. (2021). Animal Welfare Implications of Digital Tools for Monitoring and Management of Cattle and Sheep on Pasture. *Animals, 11*(3), 829.

Hewitson, Dumont, & Gordon. (2005). Response of foraging sheep to variability in the spatial distribution of resources. *Animal Behaviour, 69*(5), 1069-1076.

Hewlett, & Hibbert. (1967). Factors affecting the response of small watersheds to precipitation in humid areas. *Forest hydrology, 1*, 275-290.

Hill, Chapman, Cosgrove, & Parsons. (2009). Do ruminants alter their preference for pasture species in response to the synchronization of delivery and release of nutrients? *Rangeland Ecology & Management, 62*(5), 418-427.

Hooda, Edwards, Anderson, & Miller. (2000). A review of water quality concerns in livestock farming areas. *Science of the total environment, 250*(1-3), 143-167.

Hoogendoorn, Betteridge, Costall, & Ledgard. (2010). Nitrogen concentration in the urine of cattle, sheep and deer grazing a common ryegrass/cocksfoot/white clover pasture. *New Zealand Journal of Agricultural Research, 53*(3), 235-243.

Hosomi, & Sudo. (1986). Simultaneous determination of total nitrogen and total phosphorus in freshwater samples using persulfate digestion. *International Journal of Environmental Studies, 27*(3-4), 267-275.

Howard-Williams, Davies-Colley, Rutherford, & Wilcock. (2010). Diffuse pollution and freshwater degradation: New Zealand perspectives. *Issues and solutions to diffuse pollution*, 126-140.

Hughes. (2016). Riparian management and stream bank erosion in New Zealand. *NEW ZEALAND JOURNAL OF MARINE AND FRESHWATER RESEARCH, 50*(2), 277-290.

Hughes, Kaufmann, & Weber. (2011). National and regional comparisons between Strahler order and stream size. *Journal of the North American Benthological Society, 30*(1), 103-121.

Hutchings, Kyriazakis, Anderson, Gordon, & Coop. (1998). Behavioural strategies used by parasitized and non-parasitized sheep to avoid ingestion of gastro-intestinal nematodes associated with faeces. *Animal Science, 67*(1), 97-106.

Infascelli, Moniello, Cutrignelli, & Bovera. (2005). Vitamin and water requirements of dairy sheep. *Italian Journal of Animal Science, 4*(1), 75-83.

Jackson, Cockram, Goddard, Doherty, McGilp, & Waran. (1999). The effects of 24h water deprivation when associated with some aspects of transportation on the behaviour and blood chemistry of sheep. *Animal Welfare, 8*(3), 229-241.

Jahangir, Khalil, Johnston, Cardenas, Hatch, Butler, Barrett, O'flaherty, & Richards. (2012). Denitrification potential in subsoils: a mechanism to reduce nitrate leaching to groundwater. *Agriculture, Ecosystems & Environment, 147*, 13-23.

Jarvie, Sharpley, Withers, Scott, Haggard, & Neal. (2013). Phosphorus mitigation to control river eutrophication: murky waters, inconvenient truths, and "postnormal" science. *Journal of Environmental Quality, 42*(2), 295-304.

Jenkins, Endale, Fisher, & Gay. (2009). Most probable number methodology for quantifying dilute concentrations and fluxes of Escherichia coli O157:H7 in surface waters. *Journal of applied microbiology, 106*(2), 572-579.

Jensen, & Vestergaard. (2021). Invited review: Freedom from thirst—Do dairy cows and calves have sufficient access to drinking water? *Journal of Dairy Science, 104*(11), 11368-11385.

Johnsen, Mariussen, & Voie. (2019). Assessment of intake of copper and lead by sheep grazing on a shooting range for small arms: a case study. *Environmental Science and Pollution Research, 26*(8), 7337-7346.

Johnson. (1987). Shading behaviour of sheep: Preliminary studies of its relation to thermoregulation, feed and water intakes, and metabolic rates. *Australian Journal of Agricultural Research, 38*(3), 587-596.

Jones, Clough, Hock, & Phillips. (2008). Economic costs of hill country erosion and benefits of mitigation in New Zealand: Review and recommendation of approach. *Ministry of Agriculture and Forestry*, 79.

Jones, Collins, Naden, & Sear. (2012). The relationship between fine sediment and macrophytes in rivers. *River Research and Applications, 28*(7), 1006-1018.

Jongman, Edge, Butler, & Cronin. (2008). Reduced space allowance for adult sheep in lairage for 24 hours limits lying behaviour but not drinking behaviour. *Australian Journal of Experimental Agriculture, 48*(6/7), 1048-1051.

Jørgensen, Andersen, Berg, & Bøe. (2009). Feeding, resting and social behaviour in ewes housed in two different group sizes. *Applied Animal Behaviour Science, 116*(2-4), 198-203.

Jouven, Leroy, Ickowicz, & Lapeyronie. (2012, 01/01/). Can virtual fences be used to control grazing sheep? *RANGELAND JOURNAL, 34*(1), 111-123.

Joy. (2015). Water quality issues in New Zealand - stressed ecosystems and future solutions. *New Zealand Institute of Primary Industry Management, 19*(1), 22-27.

Joyce, & Blaxter. (1964). The effect of air movement, air temperature and infrared radiation on the energy requirements of sheep. *British Journal of Nutrition, 18*(1), 5-27.

Julian, Beurs, Owsley, Davies-Colley, & Ausseil. (2017). River water quality changes in New Zealand over 26 years: response to land use intensity. *Hydrology and Earth System Sciences, 21*(2), 1149-1171.

Julian, de Beurs, Owsley, Davies-Colley, & Ausseil. (2017). River water quality changes in New Zealand over 26 years: response to land use intensity. *Hydrology and Earth System Sciences, 21*(2), 1149-1171.

Kenyon, Maloney, & Blache. (2014). Review of sheep body condition score in relation to production characteristics. *New Zealand Journal of Agricultural Research, 57*(1), 38-64.

Lambert, Clark, Grant, Costall, & Fletcher. (1983). Influence of fertiliser and grazing management on North Island moist hill country: 1. Herbage accumulation. *New Zealand Journal of Agricultural Research, 26*(1), 95-108.

Lambert, Clark, Mackay, & Costall. (2000). Effects of fertiliser application on nutrient status and organic matter content of hill soils. *New Zealand Journal of Agricultural Research, 43*(1), 127-138.

Lambert, Mackay, Devantier, McDougall, Barker, & Park-Ng. (2003). Redefining the production potential of hill pastures using fertiliser nitrogen. *Proceedings of the New Zealand Grassland Association, 65*(1), 35-40.

Land and Water Forum. (2010). http://www.landandwater.org.nz/Site/

Lane, Tayefi, Reid, Yu, & Hardy. (2007). Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 32*(3), 429-446.

Langbein, Scheibe, & Eichhorn. (1998). Investigations on periparturient behaviour in free-ranging mouflon sheep (Ovis orientalis musimon). *Journal of Zoology, 244*(4), 553-561.

Larned, Moores, Gadd, Baillie, & Schallenberg. (2020). Evidence for the effects of land use on freshwater ecosystems in New Zealand. *NEW ZEALAND JOURNAL OF MARINE AND FRESHWATER RESEARCH, 54*(3), 551-591.

Launchbaugh, Provenza, & Pfister. (2001). Herbivore response to anti-quality factors in forages. *Rangeland Ecology & Management/Journal of Range Management Archives, 54*(4), 431-440.

Ledgard, Lieffering, Coup, & O'Brien. (2011). Carbon footprinting of New Zealand lamb from the perspective of an exporting nation. *Animal Frontiers, 1*(1), 40-45.

Lee, Jones, Moorby, Humphreys, Theodorou, & Scollan. (2001). Production responses from lambs grazed on Lolium perenne selected for an elevated water-soluble carbohydrate concentration. *Animal Research, 50*(6), 441-449.

Leiber-Sauheitl, Fuß, Burkart, Buegger, Dänicke, Meyer, Petzke, & Freibauer. (2015). Sheep excreta cause no positive priming of peat-derived CO2 and N2O emissions. *Soil Biology and Biochemistry, 88*, 282-293.

Li, Bakker, Li, Zheng, & Li. (2021). Applying a high-precision tracking system to distinguish the spatiotemporal patterns of animal movement in grassland ecology. *Biological Conservation, 255*, 109016.

LINZ. (2021). *Toitū Te Whenua Land Information New Zealand LiDAR Data base* https://data.linz.govt.nz/data/

López, Hodgson, Hedderley, Valentine, & Lambert. (2003). Selective defoliation by sheep according to slope and plant species in the hill country of New Zealand. *Grass and Forage Science, 58*(4), 339-349.

Lynch, Brown, May, & Donnelly. (1972). The effect of withholding drinking water on wool growth and lamb production of grazing Merino sheep in a temperate climate. *Australian Journal of Agricultural Research, 23*(4), 659-668.

Lynn, Manderson, Page, Harmsworth, Eyles, Douglas, Mackay, & Newsome (Eds.). (2009). *Updating and producing the land use capability survey handbook 3rd Edition*. AgResearch Ltd.

Macfarlane, Morris, & Howard. (1958). Heat and water in tropical Merino sheep. *Australian Journal of Agricultural Research, 9*(2), 217-228.

Manteca, & Smith. (1994). Effects of poor forage conditions on the behaviour of grazing ruminants. *Tropical animal health and production, 26*(3), 129-138.

Marai, El-Darawany, Fadiel, & Abdel-Hafez. (2007). Physiological traits as affected by heat stress in sheep—A review. *Small Ruminant Research, 71*(1), 1-12.

Marais, Le Roux, Wolhuter, & Niesler. (2014). Automatic classification of sheep behaviour using 3-axis accelerometer data. In *Proceedings of the annual symposium of the Pattern Recognition Association of South Africa* (Vol. 25, pp. 97-102).

Marden, Arnold, Seymour, & Hambling. (2012). History and distribution of steepland gullies in response to land use change, East Coast Region, North Island, New Zealand. *Geomorphology, 153*, 81-90.

Markwick. (2007). Water requirements for sheep and cattle. In *Profitable & Sustainable primary industry*. NSW Department of Primary Industries.

Martinez, Dabert, Barrington, & Burton. (2009). Livestock waste treatment systems for environmental quality, food safety, and sustainability. *Bioresource technology, 100*(22), 5527-5536.

Maseyk, Small, Henwood, Pannell, Buckley, & Norton. (2021). Managing and protecting native biodiversity on-farm–what do sheep and beef farmers think? *New Zealand Journal of Ecology, 45*(1).

Matsuda. (2004). River morphology and channel processes. *Fresh surface water*, 299-309.

Maurya, Sejian, Kumar, Singh, & Naqvi. (2012). Walking stress influence on livestock production. In *Environmental stress and amelioration in livestock production* (pp. 75-95). Springer.

McCoard. (2017). Issues and opportunities to capitalize on increased litter size in hill country sheep farming systems-a New Zealand perspective. *Animal Frontiers, 7*(3), 32-37.

McCoard, Wing, Smith, & Hea. (2020). Impact of the proximity of the water source on survival and growth of triplet lambs: A case study. *New Zealand Journal of Animal Science and Production, 80*, 45-50.

McColl, & Gibson. (1979). Downslope movement of nutrients in hill pasture, Taita, New Zealand: II. Effects of season, sheep grazing, and fertiliser. *New Zealand Journal of Agricultural Research, 22*(1), 151-161.

McDowell, Biggs, Sharpley, & Nguyen. (2004). Connecting phosphorus loss from agricultural landscapes to surface water quality. *Chemistry and Ecology, 20*(1), 1-40.

McDowell, Cox, & Snelder. (2017). Assessing the Yield and Load of Contaminants with Stream Order: Would Policy Requiring Livestock to Be Fenced Out of High-Order Streams Decrease Catchment Contaminant Loads? *Journal of Environmental Quality, 46*(5), 1038-1047.

McDowell, Larned, & Houlbrooke. (2009). Nitrogen and phosphorus in New Zealand streams and rivers: control and impact of eutrophication and the influence of land management. *NEW ZEALAND JOURNAL OF MARINE AND FRESHWATER RESEARCH, 43*, 985-995.

McDowell, Pletnyakov, Lim, & Salmon. (2021). Implications of water quality policy on land use: a case study of the approach in New Zealand. *Marine and Freshwater Research, 72*(4), 451-455.

McDowell, & Wilcock. (2008). Water quality and the effects of different pastoral animals. *New Zealand Veterinary Journal, 56*(6), 289-296.

McGlynn, McDonnell, Seibert, & Kendall. (2004). Scale effects on headwater catchment runoff timing, flow sources, and groundwater-streamflow relations. *Water Resources Research, 40*(7).

McKergow, Matheson, & Quinn. (2016). Riparian management: A restoration tool for New Zealand streams. *Ecological Management & Restoration, 17*(3), 218-227.

McLenaghen, Cameron, Lampkin, Daly, & Deo. (1996). Nitrate leaching from ploughed pasture and the effectiveness of winter catch crops in reducing leaching losses. *New Zealand Journal of Agricultural Research, 39*(3), 413-420.

McLennan, Rebelo, Corke, Pires Moreira, Constantino-Casas, Skillings, & Morton. (2015). Technical note: Validation of an automatic recording system to assess behavioural activity level in sheep (Ovis aries). *Small Ruminant Research, 127*, 92-96.

McMillan, Booker, & Cattoën. (2016). Validation of a national hydrological model. *Journal of Hydrology, 541*, 800-815.

Menezes-Blackburn, Giles, Darch, George, Blackwell, Stutter, Shand, Lumsdon, Cooper, & Wendler. (2018). Opportunities for mobilizing recalcitrant phosphorus from agricultural soils: a review. *Plant and Soil, 427*(1), 5-16.

Ministry for the Enviornment. (2020). National Policy Statement for Freshwater Management. *Ministry for the Enviornment*. https://www.mfe.govt.nz/publications/fresh-water/national-policy-statement-freshwater-management-2020

Monaghan, Hedley, Di, McDowell, Cameron, & Ledgard. (2007). Nutrient management in New Zealand pastures—recent developments and future issues. *New Zealand Journal of Agricultural Research, 50*(2), 181-201.

Monaghan, Manderson, Basher, Spiekermann, Dymond, Smith, Muirhead, Burger, & McDowell. (2021). Quantifying contaminant losses to water from pastoral landuses in New Zealand II. The effects of some farm mitigation actions over the past two decades. *New Zealand Journal of Agricultural Research, 64*(3), 365-389.

Monaghan, Wilcock, Smith, Tikkisetty, Thorrold, & Costall. (2007). Linkages between land management activities and water quality in an intensively farmed catchment in southern New Zealand. *Agriculture, Ecosystems & Environment, 118*(1-4), 211-222.

Monteith. (1956). Evaporation at night. *Netherlands Journal of Agricultural Science, 4*(1), 34-38.

Moriarty, & Gilpin. (2014). Leaching of E scherichia coli from sheep faeces during simulated rainfall events. *Letters in applied microbiology, 58*(6), 569-575.

Moriarty, Mackenzie, Karki, & Sinton. (2011). Survival of Escherichia coli, Enterococci, and Campylobacter spp. in sheep feces on pastures. *Applied and environmental microbiology, 77*(5), 1797-1803.

Morris. (2009). Economics of sheep production. *Small Ruminant Research, 86*(1), 59-62.

Muirhead, Collins, & Bremer. (2006). Interaction of Escherichia coli and soil particles in runoff. *Applied and environmental microbiology, 72*(5), 3406-3411.

Norton, Barnes, & Teague. (2013). Grazing management can improve livestock distribution: increasing accessible forage and effective grazing capacity. *Rangelands, 35*(5), 45-51.

O'Callaghan, Kelly-Quinn, Jennings, Antunes, O'Sullivan, Fenton, & Huallachain. (2019). The environmental impact of cattle access to watercourses: A review. *Journal of Environmental Quality, 48*(2), 340-351.

O'Flanagan, Martínez, & Errea Abad. (2011). Restoration of sheep transhumance in the Ebro Valley, Aragon, Spain. *Geographical Review, 101*(4), 556-575.

Oliver, Page, Zhang, Heathwaite, Beven, Carter, McShane, Keenan, & Haygarth. (2012). Determining E. coli burden on pasture in a headwater catchment: combined field and modelling approach. *Environment international, 43*, 6-12.

Parkyn. (2004). *Review of riparian buffer zone effectiveness* (Vol. 2005). Citeseer.

Parsons, Newman, Penning, Harvey, & Orr. (1994). Diet preference of sheep: effects of recent diet, physiological state and species abundance. *Journal of animal ecology*, 465-478.

Partington, Therrien, Simmons, & Brunner. (2017). Blueprint for a coupled model of sedimentology, hydrology, and hydrogeology in streambeds. *Reviews of Geophysics, 55*(2), 287-309.

Penning, Parsons, Orr, Harvey, & Newman. (1993). The effects of group size on grazing time in sheep. *Applied Animal Behaviour Science, 37*(2), 101-109.

Penning, Parsons, Orr, & Treacher. (1991). Intake and behaviour responses by sheep to changes in sward characteristics under continuous stocking. *Grass and Forage Science, 46*(1), 15-28.

Perry, Newman, & Thibault. (2010). Evaluation of methods used to estimate size of a population of desert bighorn sheep (Ovis canadensis mexicana) in New Mexico. *The Southwestern Naturalist, 55*(4), 517-524.

Petry, Soulsby, Malcolm, & Youngson. (2002). Hydrological controls on nutrient concentrations and fluxes in agricultural catchments. *Science of the total environment, 294*(1-3), 95-110.

Plaza, Palacios, Sánchez-García, Criado, Nieto, & Sánchez. (2020). Monitoring Spatial Behavior of Pastoralist Sheep Through GPS, LIDAR Data and Vnir Image. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 43*, 169-175.

Plaza, Sánchez, Palacios, Sánchez-García, Abecia, Criado, & Nieto. (2021). GPS, LiDAR and VNIR data to monitor the spatial behavior of grazing sheep. *Journal of Animal Behaviour and Biometeorology, 10*(2), 0-0.

Provenza, Kimball, & Villalba. (2000). Roles of odor, taste, and toxicity in the food preferences of lambs: implications for mimicry in plants. *Oikos, 88*(2), 424-432.

Putfarken, Dengler, Lehmann, & Härdtle. (2008). Site use of grazing cattle and sheep in a large-scale pasture landscape: a GPS/GIS assessment. *Applied Animal Behaviour Science, 111*(1-2), 54-67.

Pyke. (1984). Optimal foraging theory: a critical review. *Annual review of ecology and systematics, 15*(1), 523-575.

Radcliffe. (1982). Effects of aspect and topography on pasture production in hill country. *New Zealand Journal of Agricultural Research, 25*(4), 485-496.

Radeski, & Ilieski. (2017). Gait and posture discrimination in sheep using a tri-axial accelerometer. *Animal, 11*(7), 1249-1257.

Raeside, Robertson, Nie, Partington, Jacobs, & Behrendt. (2016). Dietary choice and grazing behaviour of sheep on spatially arranged pasture systems. 1. Herbage mass, nutritive characteristics and diet selection. *Animal Production Science, 57*(4), 697-709.

Ramirez, Ward, & Sreevatsan. (2004). A review of the biology and epidemiology of cryptosporidiosis in humans and animals. *Microbes and infection, 6*(8), 773-785.

Refsgaard, Thorsen, Jensen, Kleeschulte, & Hansen. (1999). Large scale modelling of groundwater contamination from nitrate leaching. *Journal of Hydrology, 221*(3-4), 117-140.

Rennie, King, Knight, Devantier, & Hoogendoorn. (2014). Improving summer and autumn feed quality in New Zealand hill country. *New Zealand Grasslands Association, 23,* 842-843.

Resource Management Act. (2020). *Resource Management (Stock Exclusion) Regulations 2020*. https://www.legislation.govt.nz/regulation/public/2020/0175/latest/LMS379869.html

Richards, Chambers, Hales, Joy, Radu, Woodward, Humphrey, Randal, & Baker. (2021). Nitrate contamination in drinking water and colorectal cancer: Exposure assessment and estimated health burden in New Zealand. *Environmental Research*, 112322.

Riseng, Wiley, Black, & Munn. (2011). Impacts of agricultural land use on biological integrity: a causal analysis. *Ecological Applications, 21*(8), 3128-3146.

Rivett, Buss, Morgan, Smith, & Bemment. (2008). Nitrate attenuation in groundwater: a review of biogeochemical controlling processes. *Water Research, 42*(16), 4215-4232.

Rouse, & Norton. (2017). Challenges for freshwater science in policy development: reflections from the science-policy interface in New Zealand. *NEW ZEALAND JOURNAL OF MARINE AND FRESHWATER RESEARCH, 51*(1), 7-20.

Rowarth, Gillingham, Tillman, & Syers. (1985). Release of phosphorus from sheep faeces on grazed, hill country pastures. *New Zealand Journal of Agricultural Research, 28*(4), 497-504.

Rusiñol, Moriarty, Lin, Bofill-Mas, & Gilpin. (2016). Human-, ovine-, and bovine-specific viral source tracking tools to discriminate between the major fecal sources in agricultural waters. *Food and environmental virology, 8*(1), 34-45.

Rutter. (2006). Diet preference for grass and legumes in free-ranging domestic sheep and cattle: Current theory and future application. *Applied Animal Behaviour Science, 97*(1), 17-35.

Saggar, Giltrap, Davison, Gibson, de Klein, Rollo, Ettema, & Rys. (2015). Estimating direct N2O emissions from sheep, beef, and deer grazed pastures in New Zealand hill country: accounting for the effect of land slope on the N2O emission factors from urine and dung. *Agriculture, Ecosystems & Environment, 205*, 70-78.

Saggar, Mackay, Hedley, Lambert, & Clark. (1990). A nutrient-transfer model to explain the fate of phosphorus and sulphur in a grazed hill-country pasture. *Agriculture, Ecosystems & Environment, 30*(3-4), 295-315.

Saini, Halverson, & Lorimor. (2003). Rainfall timing and frequency influence on leaching of Escherichia coli RS2G through soil following manure application. *Journal of Environmental Quality, 32*(5), 1865-1872.

Saint-Dizier, Lévy, & Ferreira. (2007). Influence of the mother in the development of flavored-food preference in lambs. *Developmental Psychobiology: The Journal of the International Society for Developmental Psychobiology, 49*(1), 98-106.

Samaddar, Karp, Schmidt, Devarajan, McGarvey, Pires, & Scow. (2021). Role of soil in the regulation of human and plant pathogens: soils' contributions to people. *Philosophical Transactions of the Royal Society, 376*(1834).

Sanford, Pierson, & Crovelli. (1993). An objective replacement method for censored geochemical data. *Mathematical Geology, 25*(1), 59-80.

Savadogo, Sawadogo, & Tiveau. (2007). Effects of grazing intensity and prescribed fire on soil physical and hydrological properties and pasture yield in the savanna woodlands of Burkina Faso. *Agriculture, Ecosystems & Environment, 118*(1-4), 80-92.

Schlecht, Hiernaux, Kadaouré, Hülsebusch, & Mahler. (2006). A spatio-temporal analysis of forage availability and grazing and excretion behaviour of herded and free grazing cattle, sheep and goats in Western Niger. *Agriculture, Ecosystems & Environment, 113*(1-4), 226-242.

Schlink, Nguyen, & Viljoen. (2010). Water requirements for livestock production: a global perspective. *Rev. Sci. Tech, 29*(3), 603-619.

Sheth, Benke, Kealy, Rabian, Raeside, Waters, & Hamilton. (2016). Investigation of feeding preferences of GPS monitored sheep in a binary choice experimental design under conditions of spatial uncertainty. *Journal of Spatial Science, 61*(1), 173-184.

Silungwe, Millner, & McGill. (2010). Evaluation of sorghum, sudan-grass and pearl millet cultivars in Manawatu. *Agronomy New Zealand Journal, 40*, 1-10.

Singh, Pahlow, Booker, Shankar, & Chamorro. (2019). Towards baseflow index characterisation at national scale in New Zealand. *Journal of Hydrology, 568*, 646-657.

Smith. (1989). Riparian pasture retirement effects on sediment, phosphorus, and nitrogen in channellised surface run-off from pastures. *NEW ZEALAND JOURNAL OF MARINE AND FRESHWATER RESEARCH, 23*(1), 139-146.

Sohi, Trompf, Marriott, Bervan, Godoy, Weerasinghe, Desai, & Jois. (2017). Determination of maternal pedigree and ewe-lamb spatial relationships by application of Bluetooth technology in extensive farming systems. *Journal of animal science, 95*(11), 5145-5151.

Squires. (1975). Ecology and behaviour of domestic sheep (Ovis aries): a review. *Mammal Review, 5*(2), 35-57.

Stanley, & Jones. (2003). Cattle and sheep farms as reservoirs of Campylobacter. *Journal of applied microbiology, 94*, 104-113.

Statistics. (2021). *Livestock numbers* https://www.stats.govt.nz/indicators/livestock-numbers

Stutter, Chardon, & Kronvang. (2012). Riparian buffer strips as a multifunctional management tool in agricultural landscapes: introduction. *Journal of Environmental Quality, 41*(2), 297-303.

Suckling, & Forde. (1978). I. Collection of ryegrass, browntop, and white clover. *New Zealand Journal of Agricultural Research, 21*(3), 499-508.

Swaffield, & Hughey. (2001). The South Island High Country of New Zealand. *Mountain Research and Development, 21*(4), 320-326.

Swain, Friend, Bishop-Hurley, Handcock, & Wark. (2011). Tracking livestock using global positioning systems–are we still lost? *Animal Production Science, 51*(3), 167-175.

Syers, Johnston, & Curtin. (2008). Efficiency of soil and fertilizer phosphorus use. *FAO Fertilizer and plant nutrition bulletin, 18*(108).

Tait, Miller, Rutherford, & Abell. (2017). Non-market valuation of improvements in freshwater quality for New Zealand residents, from changes in stock exclusion policy. In *MPI Technical Paper; 2017/08*. Ministry for Primary Industry.

Tait, Sturman, & Clark. (2012). An assessment of the accuracy of interpolated daily rainfall for New Zealand. *Journal of Hydrology (New Zealand), 51*(1), 25-44.

Thomas, Wilmot, Alchin, & Masters. (2008). Preliminary indications that Merino sheep graze different areas on cooler days in the Southern Rangelands of Western Australia. *Australian Journal of Experimental Agriculture, 48*(7), 889-892.

Thompson, Barry, & Dellow. (1989). The effect of selection for fleece weight upon urea metabolism and digestive function in Romney sheep. *Australian Journal of Agricultural Research, 40*(5), 1065-1074.

Thorhallsdottir, Provenza, & Balph. (1990). The role of the mother in the intake of harmful foods by lambs. *Applied Animal Behaviour Science, 25*(1-2), 35-44.

Thorrold, O'Connor, & White. (1985). Management influences on sheep behaviour, dung distribution and soil phosphate. *Proceedings of the New Zealand Grassland Association, 46*, 127-134.

Tomkiewicz, Fuller, Kie, & Bates. (2010). Global positioning system and associated technologies in animal behaviour and ecological research. *Philosophical Transactions of the Royal Society B: Biological Sciences, 365*(1550), 2163-2176.

Tozer, Douglas, Dodd, & Müller. (2021). Vegetation Options for Increasing Resilience in Pastoral Hill Country. *Frontiers in Sustainable Food Systems*, *5*, 8.

Tran, Pearson, Palmer, & Gray. (2020). Developing a landscape design approach for the sustainable land management of hill country farms in New Zealand. *Land, 9*(6), 185.

Tran, Pearson, Palmer, Lowry, Gray, & Dominati. (2022). Quantifying spatial non-stationarity in the relationship between landscape structure and the provision of ecosystem services: An example in the New Zealand hill country. *Science of the total environment, 808*, 152126.

Vale, Fuller, Procter, Basher, & Smith. (2016). Characterization and quantification of suspended sediment sources to the Manawatu River, New Zealand. *Science of the total environment, 543*, 171-186.

van der Heijden, Legout, Pollier, Bréchet, Ranger, & Dambrine. (2013). Tracing and modeling preferential flow in a forest soil—Potential impact on nutrient leaching. *Geoderma*, *195*, 12-22.

van der Weerden, Noble, Luo, de Klein, Saggar, Giltrap, Gibbs, & Rys. (2020). Meta-analysis of New Zealand's nitrous oxide emission factors for ruminant excreta supports disaggregation based on excreta form, livestock type and slope class. *Science of the total environment, 732*, 139-235.

Villalba, Manteca, & Provenza. (2009). Relationship between reluctance to eat novel foods and open-field behavior in sheep. *Physiology & Behavior, 96*(2), 276-281.

Villalba, & Provenza. (2000). Roles of flavor and reward intensities in acquisition and generalization of food preferences: do strong plant signals always deter herbivory? *Journal of Chemical Ecology, 26*(8), 1911-1922.

Villalba, Provenza, Catanese, & Distel. (2015). Understanding and manipulating diet choice in grazing animals. *Animal Production Science, 55*(3), 261-271.

Vought, Dahl, Pedersen, & Lacoursiere. (1994). Nutrient retention in riparian ecotones. *Ambio, 23*(6), 342-348.

Walling, & Fang. (2003). Recent trends in the suspended sediment loads of the world's rivers. *Global and planetary change, 39*(1-2), 111-126.

Walton, Casey, Mitsch, Vázquez-Diosdado, Yan, Dottorini, Ellis, Winterlich, & Kaler. (2018). Evaluation of sampling frequency, window size and sensor position for classification of sheep behaviour. *Royal Society open science, 5*(2), 14.

Webber, Weber, Clark, Moffet, Ames, Taylor, Johnson, & Kie. (2015). Movements of domestic sheep in the presence of livestock guardian dogs. *Sheep and Goat Research Journal, 30,* 18-23.

Wedderburn, Adam, Greaves, & Carter. (1996). Effect of oversown ryegrass (Lolium perenne) and white clover (Trifolium repens) on the genetic structure of New Zealand hill pastures. *New Zealand Journal of Agricultural Research, 39*(1), 41-52.

Weiler, & McDonnell. (2006). Testing nutrient flushing hypotheses at the hillslope scale: A virtual experiment approach. *Journal of Hydrology, 319*(1-4), 339-356.

Weiler, McDonnell, Tromp-van Meerveld, & Uchida. (2006). Subsurface stormflow. *Encyclopedia of hydrological sciences*.

Wemelsfelder, & Farish. (2004). Qualitative categories for the interpretation of sheep welfare: a review. *Animal Welfare, 13*(3), 261-268.

White, Storm, Busteed, Stoodley, & Phillips. (2009). Evaluating nonpoint source critical source area contributions at the watershed scale. *Journal of Environmental Quality, 38*(4), 1654-1663.

Wilcock, Nagels, Rodda, O'Connor, Thorrold, & Barnett. (1999). Water quality of a lowland stream in a New Zealand dairy farming catchment. *NEW ZEALAND JOURNAL OF MARINE AND FRESHWATER RESEARCH, 33*(4), 683-696.

Williams, & Haynes. (1990). Influence of improved pastures and grazing animals on nutrient cycling within New Zealand soils. *New Zealand Journal of Ecology*, 49-57.

Williams, & Haynes. (1995). Effect of sheep, deer and cattle dung on herbage production and soil nutrient content. *Grass and Forage Science, 50*(3), 263-271.

Williams, Walsh, Gormally, Walls, & Sheahan. (2010). Resource selection by hill sheep: direct flock observations versus GPS tracking. *Applied Ecology and Environmental Research, 8*(4), 279-300.

Williamson, Smith, & Quinn. (1992). Effects of riparian grazing and channelisation on streams in Southland, New Zealand. 1. Channel form and stability. *NEW ZEALAND JOURNAL OF MARINE AND FRESHWATER RESEARCH, 26*(2), 241-258.

Withers, Neal, Jarvie, & Doody. (2014). Agriculture and eutrophication: where do we go from here? *Sustainability, 6*(9), 5853-5875.

Wittenberg. (1999). Baseflow recession and recharge as nonlinear storage processes. *Hydrological processes, 13*(5), 715-726.

Wright. (2012). Water quality in New Zealand: Understanding the science. *Wellington, Ministry for the Environment*.

Xiao, Shi, Brantley, Forsythe, DiBiase, Davis, & Li. (2019). Streamflow generation from catchments of contrasting lithologies: the role of soil properties, topography, and catchment size. *Water Resources Research, 55*(11), 9234-9257.

Yang, McMillan, & Zammit. (2017). Modeling surface water–groundwater interaction in New Zealand: model development and application. *Hydrological processes, 31*(4), 925-934.

Yule, Pullanagari, Irwin, McVeagh, Kereszturi, White, & Manning. (2015). Mapping nutrient concentration in pasture using hyperspectral imaging. *Journal of New Zealand Grasslands*, 47-50.

Zahedi, Ryan, Rawlings, Greay, Hancock, Bruce, & Jacobson. (2020). Cryptosporidium and Giardia in dam water on sheep farms–An important source of transmission? *Veterinary Parasitology, 288*, 109281.

Zhong, Hoogendoorn, Bowatte, Li, Wang, & Luo. (2016). Slope class and grazing intensity effects on microorganisms and nitrogen transformation processes responsible for nitrous oxide emissions from hill pastures. *Agriculture, Ecosystems & Environment, 217*, 70-78.

Zimmer, & McGlynn. (2017). Bidirectional stream–groundwater flow in response to ephemeral and intermittent streamflow and groundwater seasonality. *Hydrological processes, 31*(22), 3871-3880.

Zimmer, & McGlynn. (2018). Lateral, vertical, and longitudinal source area connectivity drive runoff and carbon export across watershed scales. *Water Resources Research, 54*(3), 1576-1598.

Zonderland-Thomassen, Lieffering, & Ledgard. (2014). Water footprint of beef cattle and sheep produced in New Zealand: water scarcity and eutrophication impacts. *Journal of Cleaner Production, 73*, 253-262.