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HILL COUNTRY WETLAND HYDROLOGICAL CHARACTERISATION FOR NITRATE ATTENUATION

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Abstract

Nitrate attenuation in naturally occurring hill country wetlands is regulated by its hydrology, yet little is known about the hydrological characteristics of these features. This study monitored the surface water flow and quality [nitrate-N and suspended sediment (SS)] at the wetland inlet and outlet (June 2019-June 2021) and categorised the subsurface redox environment at the 0.5, 1 and 1.5 m depths (November 2019-June 2021), in a hill country wetland on a sheep and beef farm near Palmerston North, New Zealand. The wetland appears baseflow dominated, with an average annual baseflow index (BFI) of 0.65 at the wetland outlet across the two study years. However, the rainfall intensity and distribution strongly influence the hill country wetland hydrology and determine the relative role of the wetland as source/sink of nitrate-N and SS. In year 1 (June 2019-June 2020), which received disproportionately higher rainfall in winter, the wetland was a net source of nitrate-N and SS. In contrast, the wetland was a nitrate sink (29% of the inflow nitrate-N and SS loads attenuated) in year 2 (June 2020-June 2021), with an evenly distributed annual rainfall. Estimation of annual nitrate-N and SS loads using the flow-stratified technique (flowrates, ranked from the highest to the lowest, assigned to 5 decile bins) showed in general, that the high flows contributed to the highest loads in and out of the wetland. However, low flow conditions also contributed to high nitrate-N load (e.g. 8.0 kg in total in flow decile bins 2 to 5), possibly driven by grazing effects in the wetland, which was comparable to the nitrate-N load in the high flow (i.e. 9.9 kg/year in flow decile bin 1) in the outflow in the year 2. The shallow groundwater in the wetland was found to be predominantly oxic (~5 mg DO/L), however, generally low in nitrate-N (~0.5 mg/L) concentration. Subsurface nitrate reduction appears limited, as evidenced by the elevated nitrate-N concentrations (>5 mg/L), on several occasion mainly at depths of >1 m and in the spring and summer months. This study highlights that nitrate mitigation in hill country wetlands is limited mainly by the surface flow conditions, and the subsurface redox environment. Hydrological characteristics that limit nitrate reduction in hill country wetlands identified in this study, will inform the future interventions to enhance wetland nitrate attenuation in hill country pasture systems.

Introduction

Low-order streams typical of pastoral hill country, occupy a large proportion of the catchment area and account for large proportions of nitrogen (77% of national load) and suspended sediment (84% of national load) losses across NZ catchments (McDowell et al., 2017). Although the streams in headwater catchments are typically very low in nitrate-N concentration (<1 mg/L) (Burkitt et al., 2016; McColl et al., 1977), overall nitrate load magnifies as the stream network area and density increases downstream. On the other hand, pastoral activities (grazing, stock damage to stream banks, erosion of tracks) on highly erodible hill country soils make hill country farms critical source areas for suspended sediments (SS).

Hill country wetlands are common natural features in pastoral hill farms and represent a possible nature-based nitrate mitigation tool (Burns & Nguyen, 2002; Rutherford & Nguyen, 2004). Wetland hydrology plays an integral role in their nitrate attenuation function, yet a lack of understanding of their surface and subsurface hydrology characteristics limits the scope for use of hill country wetlands as edge-of-field nitrate mitigation tools in pastoral hill country farms. Hill country wetlands located in the valley-bottoms also show potential for sediment attenuation, as wetland vegetation allows entrapment and slows down the surface run-off which carries sediment from upland pastures.

This study characterised the surface and subsurface hydrology for nitrate attenuation in a pastoral hill country wetland. The objectives of this study were to (i) investigate the surface hydrology, ii) quantify the dynamics in inflow and outflow and the attenuations of nitrate-N and SS; and iii) characterise the subsurface redox environment for nitrate reduction in the hill country wetlands.

Materials and methods

Study area

The study area is a small hill country wetland (0.08 ha) located at the Massey University hill country research farm (Tuapaka) (40°21’11.8”S, 175°44’14.1”E) (Fig. 1). The sheep and beef farm is located near Palmerston North, in the lower North Island, New Zealand. The area has a humid temperate climate, with a long-term annual average rainfall of 950 mm, according to NIWA (Chappell, 2015). A perennial, second order stream flows through the wetland. An ephemeral channel directly discharges, through hillslope, into the wetland. The wetland occupies 0.3% of its catchment area (25.2 ha) that includes a directly contributing catchment area between the inlet and outlet of 1.6 ha.

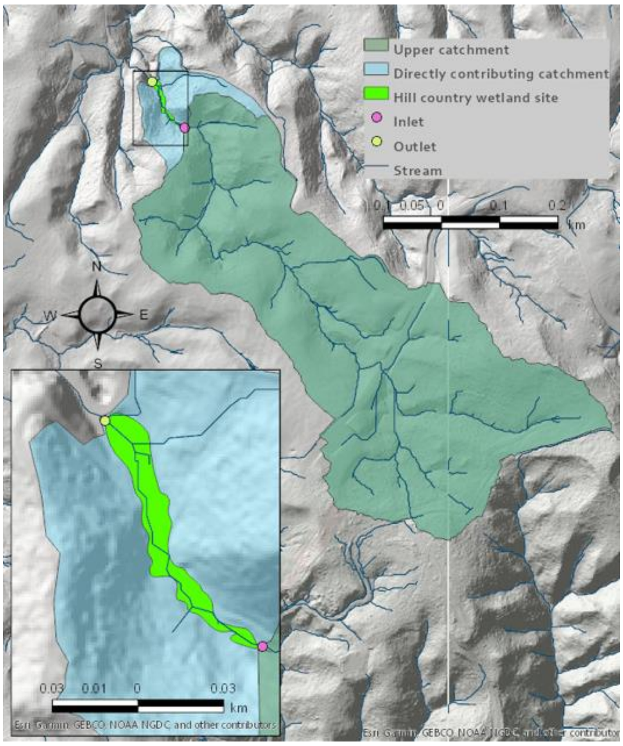

Figure 1. Map of the catchment area of the hill country wetland site at Tuapaka near Palmerston North, lower North Island, New Zealand.

Surface water monitoring

Stream flow discharge and quality were monitored at the inlet (*inflow)* and at the outlet (*outflow)* of the hill country wetland during June 2019-June 2021. The year 1 refers to the monitoring period between 1 June 2019-1 June 2020 and the year 2 refers to the period between 1 June 2020-1 June 2021. Daily rainfall depth was recorded in a local weather station near the site.

Stream flow discharge was logged at 15-min intervals using an ultrasonic doppler technique with automated Unidata Starloggers. Water quality (nitrate-N and SS) was assessed from grab samples every two weeks. Additional event-based sampling allowed high surface flow monitoring. The inflow volume retained in the wetland on a daily-basis, was calculated using the following formula:

Daily net wetland water balance = Daily inflow – Daily outflow

where +*ve* balance indicates the daily net wetland water gain, and -*ve* balance indicates the daily net wetland water loss. The annual wetland water balance is the cumulative daily net wetland water balance for a monitored year.

Annual average nitrate-N and SS loads in inflow and in outflow, were estimated using the flow-stratified technique (Elwan et al., 2018), for individual monitored years. The flow rates were ranked from the highest to the lowest and assigned to 5 flow decile bins. The average load for a decile bin is the product of the average flow rate and the average nutrient concentration in that corresponding flow bin. The total annual load is the sum of the average loads from the 5 decile bins for a monitored year.

Shallow groundwater water quality monitoring

The physico-chemical [dissolved oxygen (DO), pH] and chemical (nitrate-N, dissolved Fe, dissolved Mn, sulphate-S) properties in the shallow groundwater were monitored via piezometers (with 0.5 m screens) at the 0.5, 1 and 1.5 m depths (November 2019 – June 2021). These piezometers were located on the flowline at the upper, middle and lower wetland positions.

The shallow groundwater sampling was conducted using the national protocol for groundwater sampling in NZ (Daughney et al., 2006) with a modification made to account for low flow purging (Wilde et al., 1999) in response to the low hydraulic conductivity and long recharging times in the purged piezometers.

The subsurface redox environment was categorised based on the monitored shallow groundwater properties (McMahon & Chapelle, 2008).

Statistical analysis

Descriptive statistical analysis was conducted on the a) surface flow discharge rates, and b) shallow groundwater properties. Comparison of shallow groundwater properties between the monitored wetland depths were conducted using Analysis of One-way Variance (ANOVA) with Tukey comparison procedure at 95% confidence interval ($p \leq 0.05$) using Minitab (version 19.1.1). Plots were generated using MS Excel and R (RStudio 1.2.5033).

Results & Discussions

Flow characteristics

The hill country wetland is baseflow dominated both at inflow and at outflow. The average annual baseflow index (BFI) at the outflow, calculated across the 2 monitored years was 0.65, meaning 65% of the total annual wetland outflow was from baseflow with the remaining 35% as quickflow mainly during high flow conditions. Between the monitored years, the inflow and outflow volumes were different, but the annual baseflow volumes were similar. In general, the discharge rate was higher for outflow (median 1.1 L/s, mean 2.5 L/s, range 0.4-67.6 L/s), compared to the inflow (median: 0.41 L/s, mean: 2.1 L/s, range 0.4-93.4 L/s). This suggests that the wetland receives additional hydrological input from the direct contributing catchment area (1.6 ha), with possible routes being direct surface run-off, hillside seeps and groundwater discharge. Low flow conditions dominated the wetland as the surface outflow measured <1.4 L/s for 70% of the monitoring period (Fig. 2).

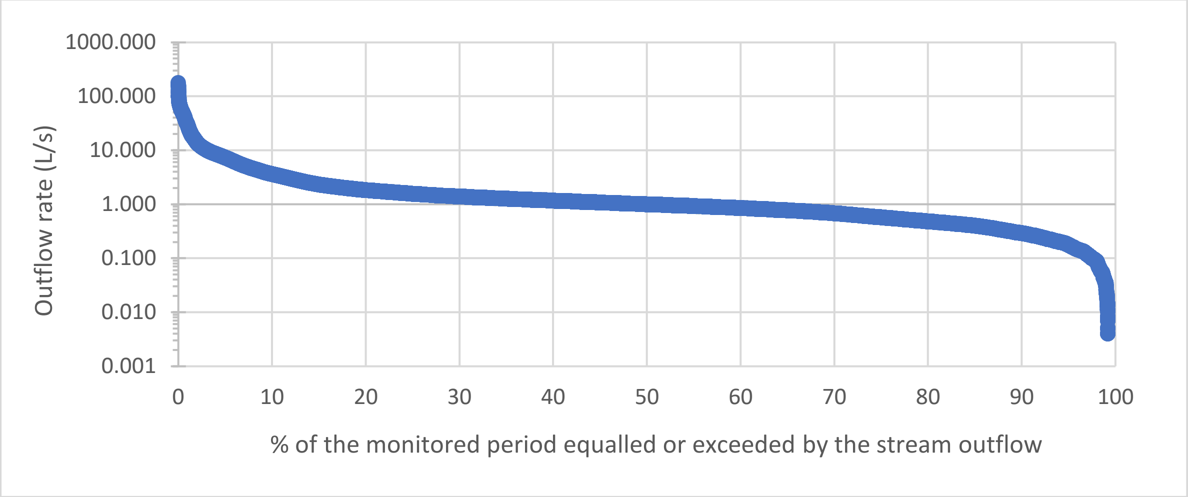

Figure 2. The flow exceedance curve of the outflow rates from the hill country wetland Tuapaka during June 2019 - June 2021.

Hydrological response to precipitation

Hill country wetland hydrology is strongly influenced by the daily rainfall depth and by the seasonal rainfall distributions (Fig. 3a, b).

For example, high daily rainfall depth, in winter and spring, drives a net wetland water loss. At the onset of such high rain events, both inflow and outflow rates rise sharply. Initially the wetland absorbs water from inflow and a temporary net wetland water gain occurs, as the

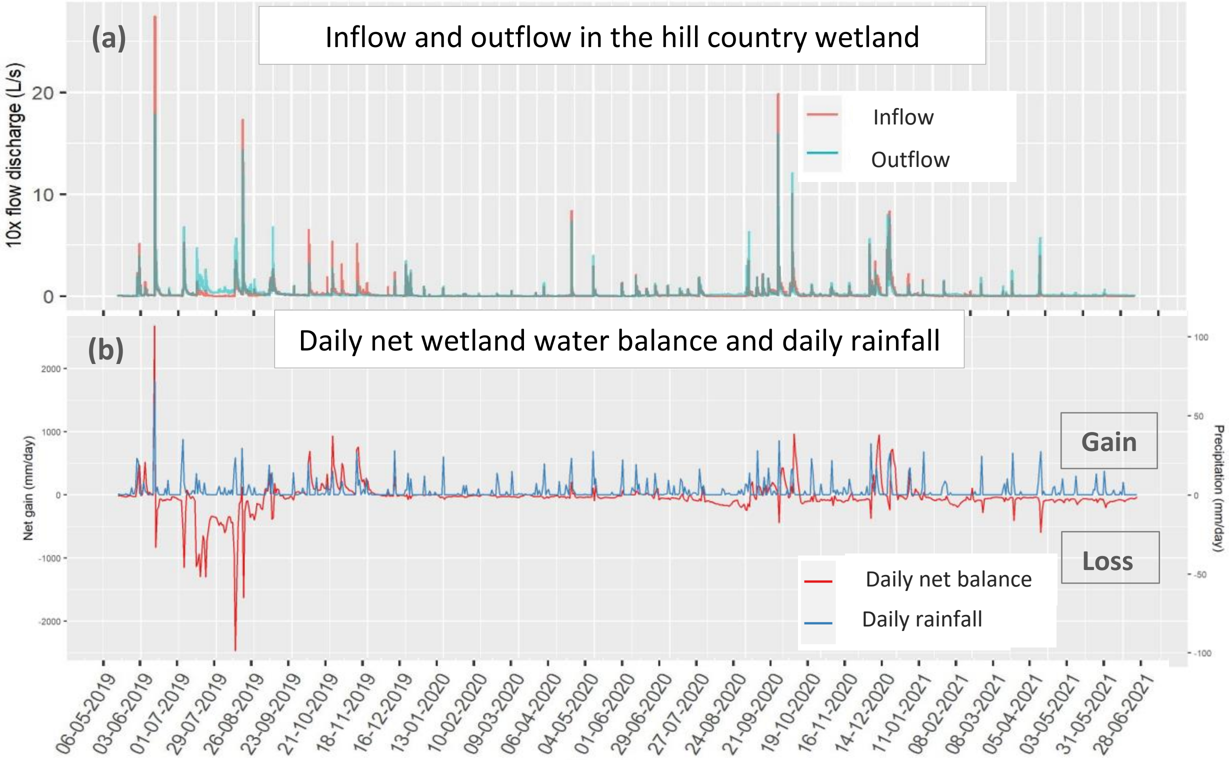

Figure 3. (a) Stream inflow and outflow rates, and (b) Daily net wetland water balance (=inflow - outflow) and daily rainfall depth in the hill country wetland at Tuapaka during June 2019 - June 2021. Gain = +*ve* net wetland water depth, Loss = -*ve* net wetland water depth.

outflow rate is lower than the inflow rate (see 13/06/2019 in Fig. 3a, b). As throughflow[1] to the wetland increases, the outflow rate exceeds the inflow rate and a prolonged net wetland water loss ensues from the wetland (see between 14/06/2019 and 16/08/2019 in Fig. 3b). This process indicates the limited flood attenuation capacity of hill country wetlands (Acreman & Holden, 2013), previously observed in fen hillslope hydrology in NZ (Bowden et al., 2001). Such wetland hydrologic response to daily rainfall depth, i.e., quick net wetland water gain followed by the prolonged net wetland water loss in response to high daily rainfall, continued between June and December in both monitored years.

The net wetland water balance has a seasonal cyclic pattern (Fig. 3b). In general, net gain in late autumn to early winter was followed by net loss in late winter. High net gains resumed in spring, while a lower net loss continued through summer.

The hydrologic fluxes in response to rainfall depth, may offer opportunities for nitrate attenuation via the interaction between high nitrate surface and subsurface flow and wetland sediments, for example, during the initial net wetland water gain in winter and spring, before the prolonged high flow results in elevated nitrate loss from the wetland.

Effect of wetland hydrology in nitrate attenuation

The annual variation in seasonal rainfall distribution affects the annual wetland hydrology, including its baseflow (Fig. 4), which in turn influences wetland nitrate attenuation. This study shows that the hill country wetland is a nitrate-N and SS source when annual rainfall is concentrated in winter, because of the high surface flow volume the rain generates that bypasses the wetland attenuation function. On the other hand, a uniform distribution of annual

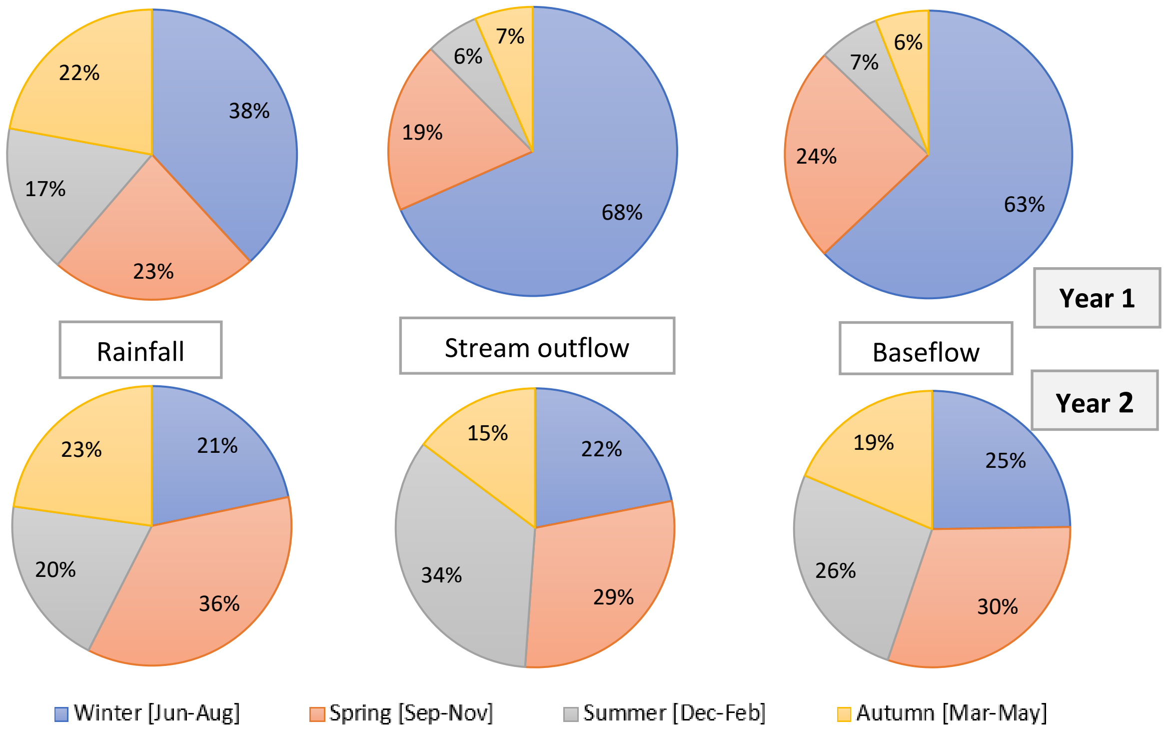

Figure 4. Comparison of the seasonal distributions (%) of annual rainfall, outflow and baseflow between year 1 (June 2019-June 2020) and year 2 (June 2020-June 2021) in the hill country wetland at Tuapaka.

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[1] Shallow subsurface component of the stormflow.

rainfall dissipates the surface inflow through the wetland throughout the year and allows for improved wetland nitrate attenuation.

For example, the annual rainfall in the catchment was similar in both monitored years (906 mm in year 1; 918 mm in year 2). However, in year 1, the wetland received a larger fraction (40%; 345 mm) of the annual rainfall during the winter months that triggered a disproportionately higher fraction (85%) of the net annual wetland water loss between June-August in that year. The fraction of the annual baseflow in the outflow was also higher during that period. Such high-volume of water over a short period of time is likely to have overwhelmed the wetlands assimilative capacity by reducing wetland water residence time. Consequently, the wetland discharged all nitrate-N and SS loads (Fig. 5) that were inputted via stream inflow. Additional nitrate-N (50% more than the inflow nitrate-N load) and SS (2% more than the inflow SS load) was discharged from the wetland over this period and was likely sourced from the direct surface run-off, hillside seeps and groundwater discharge contributing to wetland from the surrounding catchment area.

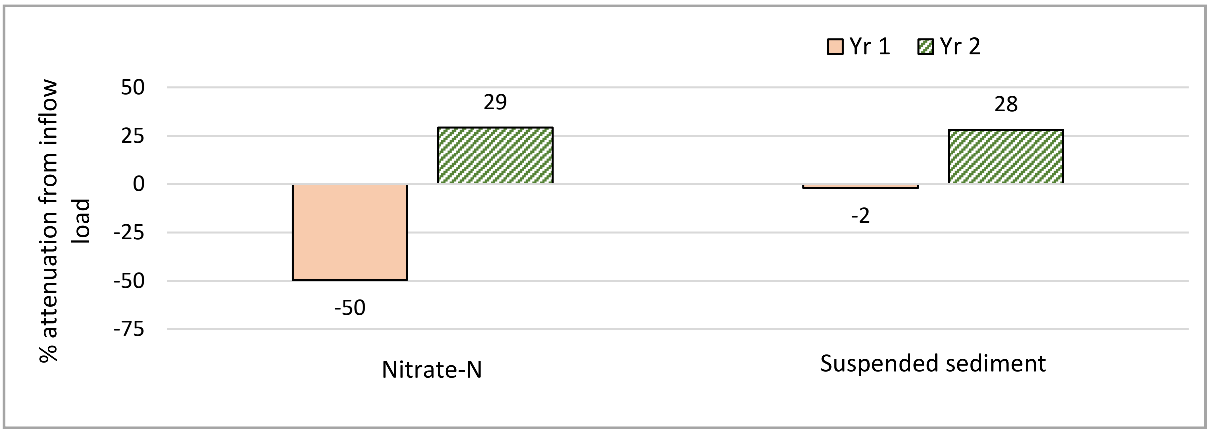

Figure 5. Percent attenuations of nitrate-N and suspended sediment from the annual inflow loads, by the hill country wetland at Tuapaka during year 1 (June 2019-June 2020) and year 2 (June 2020-June 2021).

In contrast, year 2 had a more evenly distributed annual rainfall. The wetland received only 22% (~200 mm) of the total annual rainfall and measured 26% of the net annual wetland water loss during the period June-August. This resulted in the wetland being an overall nitrate and SS sink in year 2. Overall, the wetland attenuated 29% (i.e. 1.47 kg) of nitrate-N and 28% (i.e. 1.5 ton) of SS from the inflow loads in year 2.

In year 2, less rain in winter and the more even annual rainfall distribution (Fig. 4) is likely to have driven dissipated transport of hydrological flow through the wetland, allowing for increased interaction between the nutrient inflow and the wetland substrate, as well as settling out of sediment.

This dissipated flow in the wetland not only improves the quantity but also the quality, i.e. the magnitude of wetland nutrient attenuation. For example, compared to year 1, the wetland received, 56 and 24% higher nitrate-N and SS loads in the year 2 respectively, but measured 26 and 13% less nitrate-N and SS loads at the exit respectively. This demonstrates an improvement in the magnitude of the nitrate and SS attenuation during year 2, when surface hydrology was evenly distributed through the year.

However, roughly 70% of the stream inflow nitrate-N and SS annual loads still discharged from the wetland in year 2. This highlights an opportunity for managing the wetland hydrology to improve the wetland nitrate and sediment attenuation capacity.

Flowrate contribution

In general, the high flow conditions contributed to the majority of the nitrate-N loads in inflow and outflow (Table 1a). Additionally, relatively high nitrate-N loads also occurred in low flow conditions, particularly in the outflow in the year 2. The total nitrate-N load in the lower flow decile bins (8.0 kg/year in the flow decile bins between 2 to 5) was nearly equivalent to the highest nitrate-N load measured in the highest flow bin (9.9 kg/year in flow decile bin 1) in the outflow in year 2. On the other hand, high SS loads were consistently associated to the high flow conditions throughout the monitored period (Table 1b).

Table 1a. Annual nitrate-N loads in inflow and in outflow of the hill country wetland at Tuapaka during year 1 (June 2019-June 2020) and year 2 (June 2020-June 2021), estimated by the flow-stratification technique, with flowrates ranked from the highest to lowest and assigned to 5 flow decile bins.

		Average nitrate-N load for flow deciles (kg/year)					**Total nitrate-N load (kg/year)**	**Highest 20% flow (flow decile bin 1)**	**Below 80% flows (flow decile bins 2 to 5)**
		1	**2**	**3**	**4**	**5**			
Year 1	**Inflow**	12.9	2.6	0.3	0.2	0.1	**16.1**	12.9	3.2
	Outflow	22.1	1.0	0.3	0.5	0.1	**24.1**	22.1	2.0
Year 2	**Inflow**	22.9	0.5	0.2	1.3	0.3	**25.2**	22.9	2.3
	Outflow	9.9	0.6	2.1	4.3	1.0	**17.8**	9.9	8.0

Table 1b. Estimates of suspended sediment loads in inflow and outflow of the hill country wetland at Tuapaka during year 1(June 2019-June 2020) and year 2 (June 2020-June 2021), estimated by the flow-stratification technique, with flowrates ranked from highest to lowest and assigned to 5 flow decile bins.

		Average suspended sediment load (SS) for flow deciles (t/year)					**Total SS load (t/year)**	**Highest 20% flow (flow decile bin 1)**	**Below 80% flows (flow decile bins 2 to 5)**
		1	**2**	**3**	**4**	**5**			
Year 1	**Inflow**	22.3	0.038	0.017	0.024	0.005	**22.4**	22.4	0.08
	Outflow	22.8	0.015	0.015	0.006	0.004	**22.8**	22.8	0.04
Year 2	**Inflow**	24.9	2.701	0.010	0.054	0.005	**27.7**	24.9	2.77
	Outflow	19.4	0.039	0.387	0.077	0.017	**20.0**	19.4	0.52

This study affirms the incremental nitrate-N and SS loads which accrue with increasing catchment size. A 3.5 times larger sub-catchment area (85 ha) on the same farm discharged a 10 times higher nitrate-N load (1.28 kg/ha/year) (Burkitt et al., 2016), compared to the load (0.17 kg/ha/year from a 25.2 ha catchment area) measured in the current study. A catchment area which was 7 times larger (180 ha) on the same farm, measured 10 times larger SS loads (1.4 t/ha/year) (Bargh, 1976), compared to the current study (0.2 t/ha/year). These comparisons highlight the importance of headwater catchments to nutrient and sediment loss and the potential for headwater hill country wetlands to contribute to contaminant attenuation within catchments. However, to maximise their attenuation potential, a sound understanding of the local wetland hydrology, including its flow characteristics and subsurface contributions, is fundamental (Hill, 2019; Woodward et al., 2013).

Shallow groundwater water physico-chemical properties

The shallow groundwater in the hill country wetland was predominantly oxic, with a mean dissolved oxygen (DO) of 5.5 mg/L, a near neutral median pH of 6.4-6.5, predominantly low nitrate-N concentration (median: 0.3-0.5 mg/L), but with abundant supply of available electronic donor (mean values: 5.8-11.65 mg DOC/L, 14.1-29.3 mg Fe^{2+}/L and 2.7-4.1 mg Mn^{2+}/L) in the three monitored depths (Fig. 6). The comparatively higher subsurface DOC concentration measured in this study, could be from the grassy vegetation in the wetland, as an elevated DOC (2.4 mg/L) in shallow groundwater was recorded near the wetland, in contrast to low DOC concentrations (1.1 mg/L) measured in deeper groundwater in a dairy pastoral catchment (Stenger et al., 2008).

The very few events with low DO concentration (<2 mg/L) were mainly at the 1.5 m depth. Elevated nitrate-N concentrations (>5 mg/L) were measured mainly at the >1 m depths on several sampling occasions in summer, suggesting the influence of grazing animals within the wetland.

The subsurface redox categorisation further confirmed predominantly oxic groundwater (threshold criteria: >2 mg DO/L) in all depths (McMahon & Chapelle, 2008). The only deviations from this general trend were 5 occurrences of mixed oxic-anoxic (3 O_2-Fe (III)/sulphate-S and 2 O_2-methane events), 3 mixed oxic-anoxic (1 O_2-Fe^{3+}/sulphate-S and two O_2-methane) and 3 suboxic and 1 anoxic occurrence, respectively, at the 0.5, 1 and 1.5 m depths out of their corresponding 75, 47, 64 successful sampling events.

Subsurface nitrate-N reduction in the study area is likely to be limited by its aerobic condition. With increasing depth, mean DO decreased but remained >5 mg DO/L at all depths, whereas <2 mg DO/L is considered ideal for nitrate reduction (Korom, 1992; Thayalakumaran et al., 2008). However, the abundant supply of different species of electron donor in the subsurface depths, with significantly higher DOC (11.65 mg/L) at the 0.5 m depth and significantly higher Fe^{2+} observed at the 1 m depth, shows the subsurface nitrate reduction by denitrification is unlikely to be limited by electron donor.

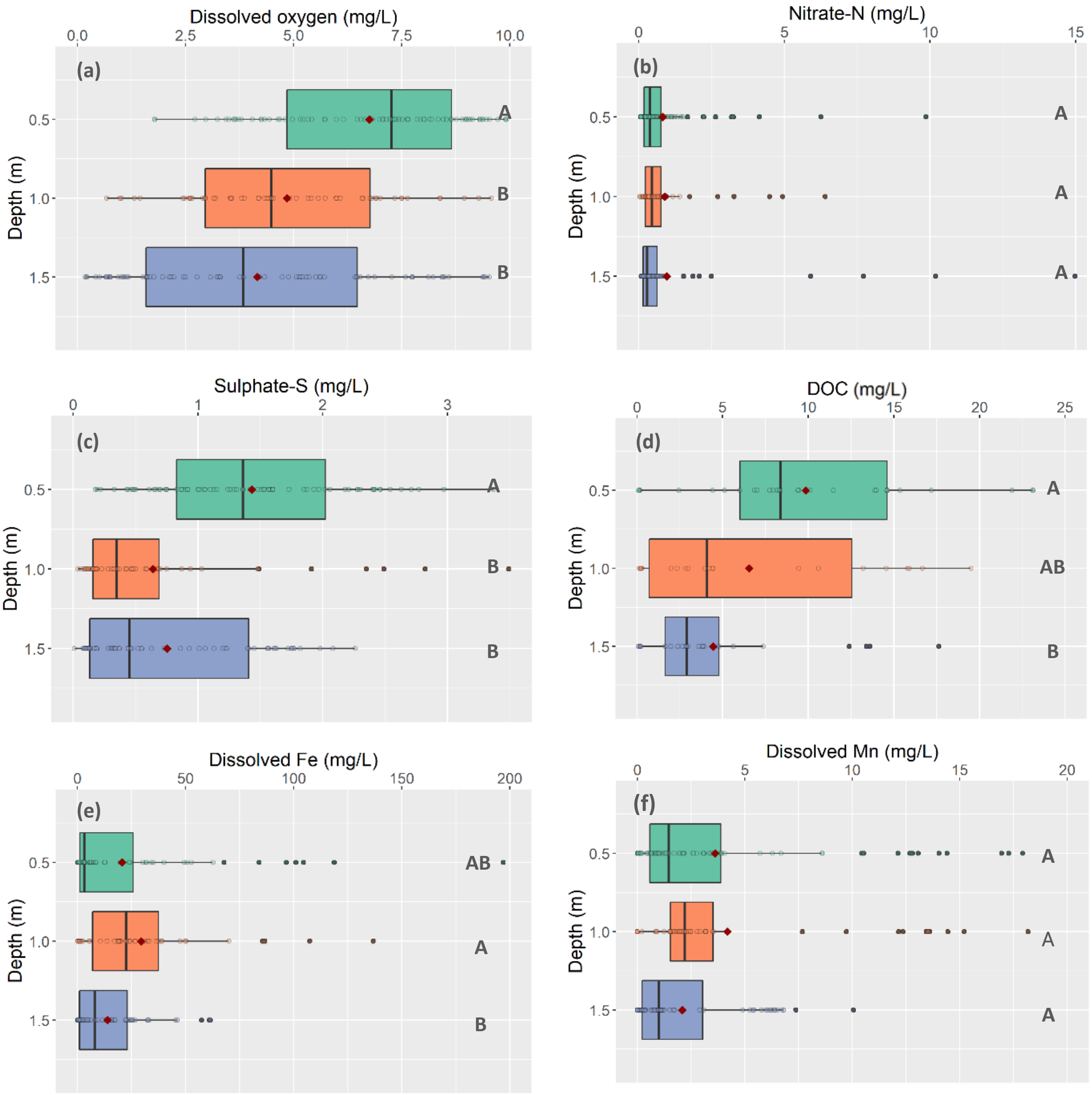

Figure 6. Boxplots present the (a) dissolved oxygen (DO), (b) nitrate-N, (c) sulphate-S, (d) dissolved organic carbon (DOC), (e) dissolved Fe and (f) dissolved Mn concentrations measured in shallow groundwater at the 0.5, 1 and 1.5 m depths in the hill country wetland at Tuapaka during the study. The first and the third quartiles represent the 25% and 75% of the measured values, respectively. Median values are indicated by the straight line inside the boxes. The red diamond shows the mean values. Letters within the boxplots refer to mean concentration variances between depths, with different values representing significant differences at $p \leq 0.05$.

Conclusions

The estimated nitrate-N and sediment attenuations clearly show there is opportunity for improvement in the attenuations in hill country wetlands. The hydrological response to daily rainfall depth and their seasonal distribution play an important role in the nitrate and SS attenuation functions in hill country wetlands, which determines the relative role of wetland as a source/sink of nitrate-N and SS in the pastoral landscape.

While the majority of the nitrate-N and the SS loads occur in high flow conditions, substantial nitrate-N load can also occur in low flow, likely from grazing activities. The predominantly oxic condition in shallow groundwater may add to the challenges for nitrate reduction in the surface-flow dominated hydrology of hill country wetlands. The wetland in low flow conditions common in the dry seasons, measured (1) high nitrate-N load in the outflow, and (2) elevated nitrate-N in oxic shallow groundwater. Wetland drainage manipulation that facilitates a nitrate reducing environment in the wetland, targeted to particularly the low flow conditions in drier seasons is likely to improve nitrate attenuation in pastoral hill country wetlands.

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