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RESEARCH

LiDAR reveals drains risks to wetlands have been under-estimated

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Abstract: Drainage is a recognised cause of wetland loss worldwide, and New Zealand is no exception. In the last 200 years drainage has reduced the natural extent of wetlands in New Zealand by c. 90%. Avoiding further loss is a national priority. Despite recent reform to restrict new drains within 100 m of existing wetlands in New Zealand, little is known about the extent and effect of existing drains in and near wetlands. Using a national layer of wetland extent (Freshwater Ecosystems of New Zealand) we calculated the area of wetlands currently within a zone of potential drain effects in the North and South Islands, by buffering an existing national drain layer by 100 m and 50 m and stratifying these results by peat/non-peat, and wetland type. We show that 7476 ha (c. 3%) of New Zealand wetlands identified in the national FENZ dataset are potentially affected by drainage when intersected with the national drains layer buffered by 100 m. Of these wetlands near drains, 4387 ha were wetlands with high organic matter (peat) that are vulnerable to drainage-induced subsidence and release of greenhouse gases. We then conducted a case study within the Waituna catchment (Southland, New Zealand) to assess if the national drain data is under-estimating the extent of wetland drainage by comparing the area affected by drainage detected using the national drains layer with an algorithm to identify drains from LiDAR. Our catchment case study revealed that our LiDAR method more than tripled the area of wetland near drains suggesting that the existing national drains layer is underestimating wetland drainage extent. We highlight that further work should be undertaken to develop an accurate stocktake of drains near wetlands, given the increasing availability of LiDAR and the ongoing efforts to improve wetland mapping by territorial authorities.

Keywords: bog, drainage, ecological resilience, fen, peat subsidence, spatial modelling

Introduction

Drainage is one of the primary causes of wetland loss and degradation globally (Zedler & Kercher 2005; Davidson 2014). New Zealand wetlands have experienced far-reaching ecological impacts from drainage and lowered water tables (Robertson et al. 2019). Ecological impacts of a lowered water table due to drainage have been documented in New Zealand wetlands including: (1) the loss of *Sporadanthus* cover, with increased *Empodisma* and woody *Epacris* cover, reducing ecological resilience (Clarkson et al. 2020), (2) declines of native wetland plant species diversity due to invasion of fast-growing exotic species (Sorrell et al. 2007), and (3) wetland loss and degradation (Myers et al. 2013). A desktop analysis of wetland condition and extent in New Zealand found that wetland ecological condition was negatively correlated with drains near and within wetlands (Ausseil et al. 2011). More specifically, wetlands on peat are particularly sensitive to lowered water tables and can effectively subside and shrink when drained, causing large-scale land management problems (Pronger et al. 2014), loss of ecological resilience (Harris et al. 2020), and increased greenhouse gas emissions (Leifeld et al. 2019). The effect of drains on peat wetlands differs according to factors such as drain depth and soil physical parameters, but subsidence has been detected 100 m from deep (2 m) drains that are at hydrological equilibrium (Fitzgerald et al. 2005).

In New Zealand, recent regulations effectively restrict establishment of drains near wetlands that will have ecological impacts (Resource Management [National Environmental Standards for Freshwater] Regulations 2020). However, these regulations do not deal with the mitigation or remediation of impacts from existing drains, some of which may be actively maintained via existing use rights; see an example of existing use being claimed in Hancock (2021). Despite the availability of a national-scale drains geospatial layer, to our knowledge, there has been no stocktake of the area of wetlands, including peat wetlands, affected by drains in New Zealand—information that is necessary to determine the risk of ongoing wetland

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degradation. Furthermore, the accuracy of this drains layer has not been determined or compared against other measurements of drainage including LiDAR (light detection and ranging), which is a promising technique for identifying open-ditch (surface) drains across large areas (e.g. Carless et al. 2019). LiDAR provides high resolution data of ground surface elevation across large areas, meaning small changes in elevation (e.g. due to drains) are readily apparent.

In this paper, we quantify the extent of wetlands in New Zealand that are proximate to surface drains. Firstly, we use national-scale drains geospatial data to calculate the area of wetlands (as mapped by Freshwater Ecosystems of New Zealand [FENZ], a national-scale wetland layer) near drains. We report the area of wetlands near drains for all types of wetlands nationally, and a subset of wetlands identified as being on a peat substrate by FENZ (i.e. peatlands), to help understand the area that may be contributing to larger amounts of greenhouse gas emissions and contributing to climate change. We then consider the accuracy of information in the national drains layer by comparing the extent of drains and area of wetland near drains to a LiDAR drain dataset using a case study of the Waituna Lagoon catchment, Southland, which has excellent LiDAR coverage.

Methods

Data layers

We used the "current wetland extent" layer from the FENZ geospatial database which includes wetland type and peat/non-peat status (Ausseil et al. 2011); source data available from the Department of Conservation (https://www.doc.govt.nz/our-work/freshwater-ecosystems-of-new-zealand/). Minimum wetland polygon size was 0.5 ha.

We used the Land Information New Zealand (LINZ) drains layer as our national-scale surface drains layer. As this is updated periodically (https://data.linz.govt.nz/layer/50262-nz-drain-centrelines-topo-150k/), we archived the layer we used with the data for this paper (see data availability). We recognise that this does not capture sub-surface drainage features.

We used a case study of the Waituna Lagoon catchment, Southland, where we compared (1) national-scale data (above) for the catchment with (2) catchment-scale LiDAR data, sourced from the regional council for Southland, Environment Southland.

Data analysis

We chose to calculate a potential area of impact around drains using 100 m and 50 m buffers. These distances were chosen with regard to both regulations and scientific evidence (detailed below). New Zealand regulations (Resource Management [National Environmental Standards for Freshwater] Regulations 2020) make earthworks and the diversion of water within 100 m of a wetland a non-complying activity (regulation 52), meaning there is a very high threshold to obtain a resource consent.

Justification of buffer width

For a drain 2 m deep, Fitzgerald et al. (2005) calculated that 50 m from that drain, peat subsidence was > 30 cm for drains considered to be at equilibrium (effects of drains on subsidence vary with time since drainage; see discussion in Schipper and McLeod (2002)). In terms of the distance decay of ecological effects, work at the highly modified Dunearn peat bog (Southland) suggested that *Empodisma*, a key peat-forming species, increased in abundance with distance from drains out to > 150 m with no sign of a plateau (raw data interpretation, linear model used in Ledgard G, Department of Conservation, unpubl. data). At Otakairangi (Northland) a central drain bisecting the bog has created a 'swamp belt' through the wetland, 10–30 m wide in some areas but extending to 200 m in others. The drain affects water level nearby (< 20 m from drain for drawdown) but also carries nutrient rich floodwaters into the central portion of the bog (Douglas 2019). At Moanatuatua wetland (Waikato), drains surround the outside of the wetland. While water table impacts were most pronounced within 20 m, permanent lowering of the water table was observed up to 195 m from edge drains (Daws 2018). Furthermore, earlier work at Moanatuatua (three years after drain deepening) highlighted an initial dramatic change followed by some stabilisation (Clarkson et al. 1999). Internationally, changes in peat and vegetation have been observed up to 60 m from drains in a study of 24 wetlands (Poulin et al. 1999), while other studies focussing on hydrology have found a range of distances within which a noticeable effect occurs from 0.5 m to 320 m (Boelter 1972; Roy et al. 2000; Holden et al. 2004; Paal et al. 2016).

As such, we consider 100 m to be reasonably conservative 'zone of potential effect' from drains, that in addition, coincides with the trigger distance for drainage activities to be rendered potentially non-complying in terms of environmental regulations.

National-scale analysis

The LINZ drains layer includes a total of 25 339 km of drains across the country (25 311 km when scope is restricted to only the North and South islands). We buffered the LINZ drains layer by 100 m and 50 m, effectively creating polygons of just over 100 and 200 m width respectively (except where buffered drains overlapped). We then intersected the buffered LINZ drains layer with the FENZ layer, stratifying by wetland type and peat content. Wetland type was applied by the FENZ layer using New Zealand definitions (Johnson & Gerbeaux 2004). In brief, the main New Zealand wetland types discussed in this paper include bog, fen, swamp, and marsh, where bogs are lower nutrient, lower pH, rainfed, peat-dominated, with little water fluctuation; marshes and swamps are higher nutrient, higher pH; and marshes are distinguished from swamps by having greater water fluctuations, better drainage and thus an overall lower water level, and more mineral substrate than swamps. Fens sit between bogs and swamps in this continuum. This intersection gave us the area of wetland within 100 m and 50 m of drains as mapped by the LINZ drains layer. As FENZ does not classify the peat status of wetlands on Stewart Island and there are no soils or drains layer for this island, our results are limited to the main North and South islands. It should also be noted that unmapped wetlands are not included in this analysis and that ongoing delineation of wetlands, as required of territorial authorities across New Zealand, will expand the inventory of wetlands that could be assessed for drainage impacts.

Creating and validating LiDAR drain model

A detailed discussion of the model methodology is provided in Appendix S1 in Supplementary Material; we provide a summary here. This analysis compares the LINZ drains layer with a LiDAR-derived surface drains layer in the Waituna

Lagoon catchment as a case study. Given the preliminary nature of the model and the lack of national scale LiDAR coverage we do not attempt to extrapolate to the rest of the country.

We modified an existing method to map drains using LiDAR, which involved random forest models with training and testing data (Roelens et al. 2018), and then post-processing. Training points are data used to teach the model what features in the landscape are considered drains and are used to build the model. Conversely, testing points are not used in model building, but are used after the model is built, to assess model performance. The model included predictors relating to landform relief: slope, slope height, standardised height, normalised height, valley depth, topographic position index (the relative position of a pixel in relation to a given neighbourhood), mid-slope position, and local relative elevation. We applied a filter to exclude some very small polygons. After this, we used a second method where we generated 120 circles of 5 ha each within the study area and compared the results of the model to a manually digitised drains layer for each of those circles. The digitised layer was created using aerial imagery (ESRI basemap NZ imagery; resolution ranges 0.075–1.25 m; and some 10 m imagery where more detailed not available; the digitised area had good resolution which was primarily sourced from data with 0.4 m resolution on inspection) and two layers from the model: local relative elevation and topographic position index. Six circles were excluded for not falling fully within the study area, leaving 114 circles in total. These circles were randomly located, rather than targeting areas of wetland, meaning multiple circles contained no wetland, or no drain (see Appendix S3).

We assess the model results using the following metrics:

(1) Overall agreement: the area mapped as drain by both methods (LiDAR and manually digitised), added to the area mapped as 'not drain' by both datasets, divided by the total area considered (effectively 114 × 5 ha).

(2) Overall omission: the amount of drain not detected by the LiDAR; this can be expressed as area (total area omitted/total area of false negative), or as a percent (area omitted, out of the validated area of drain). Overall omission describes the percentage of drain missed.

(3) Overall commission: the amount of drain identified by the LiDAR model that was not identified by the manually-digitised method; this can be expressed as area (total area of commission/total area of false positive), or as a percent. In this case, we calculated the percentage using the area of commission divided by the total area identified as drain by the model (including the false positive). This effectively describes how much of the area the model identified as drain is incorrect. This formulation avoids dividing by zero (which might occur where the model identifies some drain in a polygon, but the validation exercise does not).

We do not attempt to modify the whole-study-area results with these validation results on a subset of the study area. Instead, we assess the effect of the omissions and commissions of drains, by quantifying the difference in area of wetland within 100 m of a drain, for the 114 ha that were assessed using both the LiDAR model and the manually digitised technique. This allows the magnitude of omission and commission to be assessed: where, for example, commissions or omissions (false positives and false negatives) occur far from wetlands, then they will have little effect on the variable of interest.

Results

National-scale dataset

There are 249 611 ha of wetlands remaining in New Zealand, according to the FENZ current wetland extent layer, which had a minimum polygon size of 0.5 ha. After we restrict this data set to the North and South Islands of New Zealand to exclude Stewart Island, there are 235 598 ha of wetlands mapped by FENZ as remaining in mainland New Zealand. The total area of wetland within 100 m of a drain is 7476 ha; this is 3% of the total area mapped as wetland using FENZ. This 7476 ha of wetland near drains is categorised into wetland types in Table 1.

The total 235 598 ha of wetland includes 88 950 ha of swamp, 53 973 ha of pakihi, 32 924 ha of bog, 31 789 ha of fen, and 22 733 ha of marsh with the remaining 5230 ha in gumland, seepage, and inland saline wetlands. Of these totals, the following area of current wetland is on peat substrate: 32 723 ha of bog, 18 684 ha of swamp, 3616 ha of fen, 423 ha of gumland, and 145 ha of pakihi. There were no marsh, seepage, or inland saline wetlands mapped on peat.

Area of wetlands within 100 m of a drain: all substrates

Of the total 7476 ha of wetlands near drains, there are (in order of area; refer Table 2) 3692 ha of swamps near drains (4% of all swamps mapped by FENZ), 2208 ha of bogs near drains (7% of all bogs mapped by FENZ; see Fig. 1), 957 ha of fens near drains (3% of all fens mapped by FENZ), and 288 ha of pakihi near drains (0.5% of all pakihi mapped by FENZ). There was additionally a total of 331 ha of the remaining wetland types near drains (gumland, inland saline, marsh, and seepage).

Table 1. Area of wetland (ha) within 100 m and 50 m of a drain in New Zealand. Distance from drain indicated by buffer distance. Area given by wetland type and peat content of soil. Numbers reported in text for peatland include peat only, and do not include the mix of peat and mineral soil.

Buffer distance	Substrate	Swamp	Bog	Fen	Pakihi	Marsh	Gumland	Seepage	Inland saline
100 m	Peat	1532	2204	628	0	0	23	0	0
100 m	Mix of peat and mineral soil	192	4	9	28	0	0	0	0
100 m	Mineral soil	1968	0	319	260	281	22	5	1
50 m	Peat	779	1133	325	0	0	12	0	0
50 m	Mix of peat and mineral soil	95	1	5	16	0	0	0	0
50 m	Mineral soil	992	0	163	129	134	11	2	0

Area of wetlands within 100 m of a drain: specifically, peat substrates

Once we restrict our results to wetlands on peat substrate, using only the FENZ national-level dataset, the area of peat bog (bog on peat substrate) within 100 m of a current drain is 2204 ha (Table 2). This is 7% of the total area mapped as peat bog by FENZ (Table 2). The area of peat swamp (swamp on peat substrate) within 100 m of a current drain is 1532 ha.

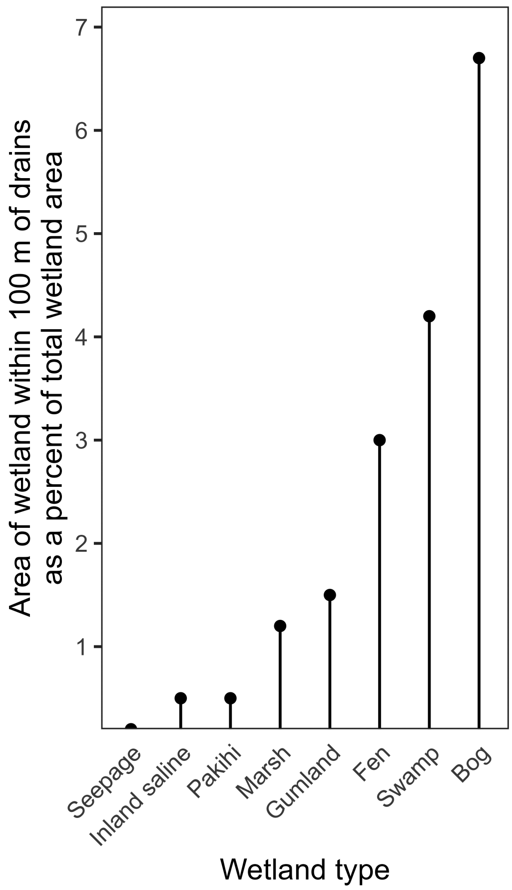

Figure 1. Area of wetlands (all substrates) within 100 m of a drain, by wetland type. Both drains and wetlands use the national-scale FENZ and LINZ layers. See Table 2 for more details, and the same breakdown for percent of wetlands on peat that are near drains.

This is 8% of the total area mapped as peat swamp by FENZ. Combined, there are 4387 ha of peat wetland within 100 m of a drain in New Zealand.

Case-study of the Waituna catchment

Our LiDAR layer identified more features of the landscape as drains than the LINZ drains layer (see Figs 2–4), and also identified smaller water features that appeared near the edges of lakes that were not captured in the LINZ drains layer. In this analysis, we report total wetlands only (i.e. all substrates).

For the Waituna catchment, the LiDAR mapping of drains revealed up to 487% more wetland within 100 m of a drain (average 226%) than the LINZ drains layer (Fig. 5). Note these percentages are percentage increase and as such, a 100% increase reported here is equivalent to a doubling in area detected. These totals of wetlands near drains in the Waituna catchment can be partitioned into wetland type: we found 1131 ha of bogs to be within 100 m of a drain when using the LiDAR dataset, compared with 304 ha when using the LINZ drains layer. Similarly large differences were found for swamps (478 ha LiDAR dataset vs 187 ha LINZ drains layer) and fens (176 ha LiDAR dataset vs 30 ha LINZ drains layer). Overall, the LiDAR dataset picked up a total of 1892 ha of wetlands within 100 m of drain in the Waituna catchment, compared with 580 ha when using the LINZ drains layer. There are 5452 ha of wetlands mapped by the national-scale FENZ layer within the catchment. Of this area, 35% of wetlands within the catchment were within 100 m of a drain using the LiDAR dataset, compared to only 11% of wetlands (by area) when using the LINZ drains layer.

Post-hoc comparisons of the LiDAR model to manually digitised drain layers within the catchment validation areas (114 in total) indicated an overall agreement metric of 98.8%, where ‘agreement’ is the area of agreement of ‘drains’ and ‘not-drains’, divided by the total area considered. Of the 570 ha considered in the manual digitisation test of the LiDAR dataset, 6.3 ha were identified as drain by both methods and 557 ha were considered to be not drain by both methods. Across the area tested using manual digitisation, a total of 1.97 ha of drain was missed by the model (false negative) and a total of 5.17 ha was included by the model but not by the manually digitised method. Overall omission (false negatives) was 23.9% (± 2.43), which is to say that of the total area tested, 24% was missed by the model. Overall commission (false positives)

Table 2. Area of wetland (ha), and peatland (ha) within 100 m of a drain in New Zealand, by wetland type. Area wetlands total is the total area of that wetland type, for mainland New Zealand (North and South islands). Percent near drains is the percentage of the total area, divided by the area within 100 m of a drain. Rows are ordered by the last column (% peatland near drains).

Wetland type	Area wetlands near drains	Area wetlands total	% wetlands near drains	Area peatlands near drains	Area peatlands total	% peatlands near drains
Fen	957	31 789	3.0	628	3616	17.4
Swamp	3692	88 950	4.2	1532	18 684	8.2
Bog	2208	32 924	6.7	2204	32 723	6.7
Gumland	44	2900	1.5	23	423	5.4
Pakihi	288	53 973	0.5	0	145	0
Inland saline	1	292	0.5	0	0	-
Marsh	281	22 733	1.2	0	0	-
Seepage	5	2038	0.2	0	0	-

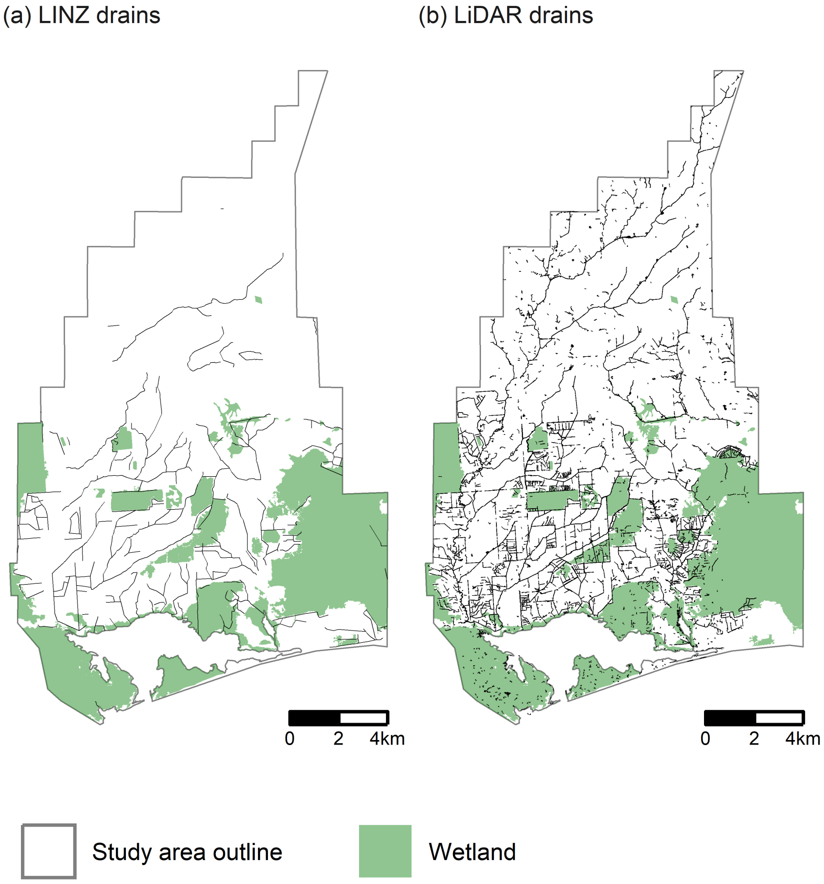

Figure 2. Extent of drains in the national scale layer (LINZ drains) and the LiDAR dataset derived for our Waituna case study (LiDAR drains). Note some overlap in (b) with likely river features in the north of the image, and some smaller polygons within the south-west of the image that are likely areas near small natural ponds.

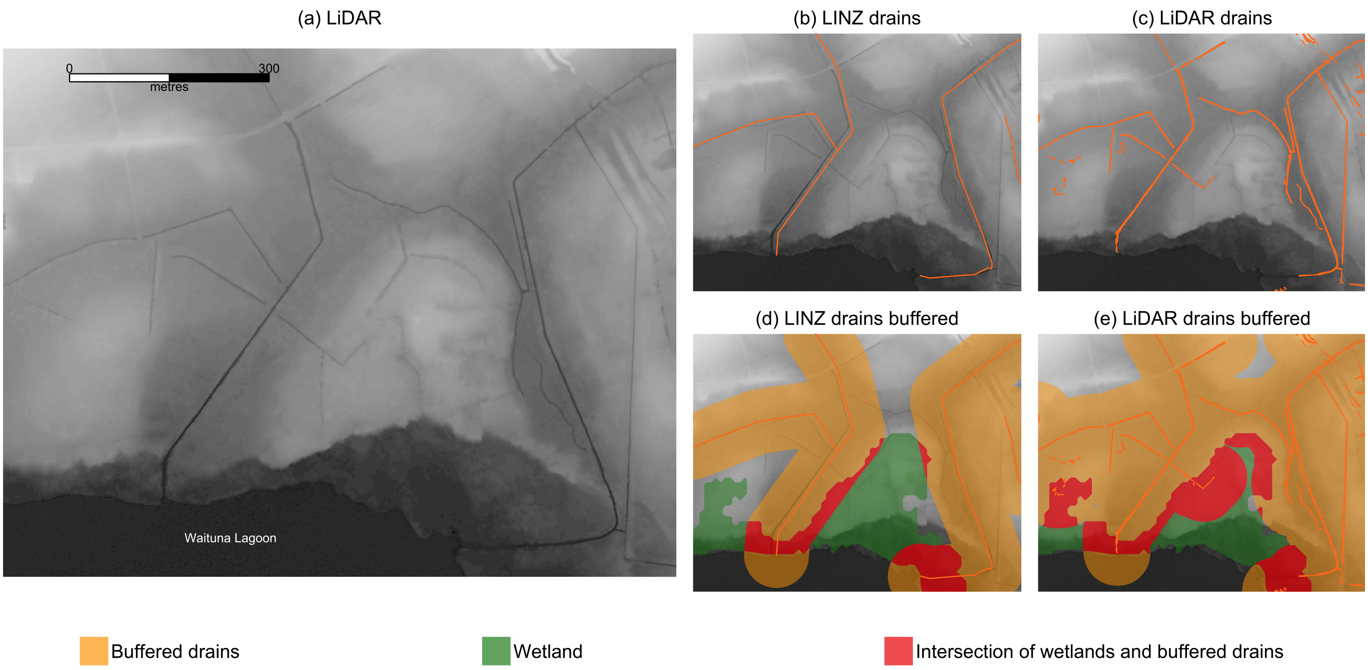

Figure 3. Example 1: (a) LiDAR image, which is the base image in all other panels; (b) LINZ drain coverage, clearly showing many missed drains; (c) LiDAR drain coverage with some drains missing, but also a river channel mapped as a drain; (d) LINZ drain coverage buffered by 100 m, showing a small overlap between drains and wetlands; (e) LiDAR drain coverage buffered by 100 m, showing substantial overlap (red) between areas mapped as wetland by FENZ, and the buffered drains. Centre of this image is NZTM easting 1258418, NZTM northing 4840540; to the north of Waituna Lagoon.

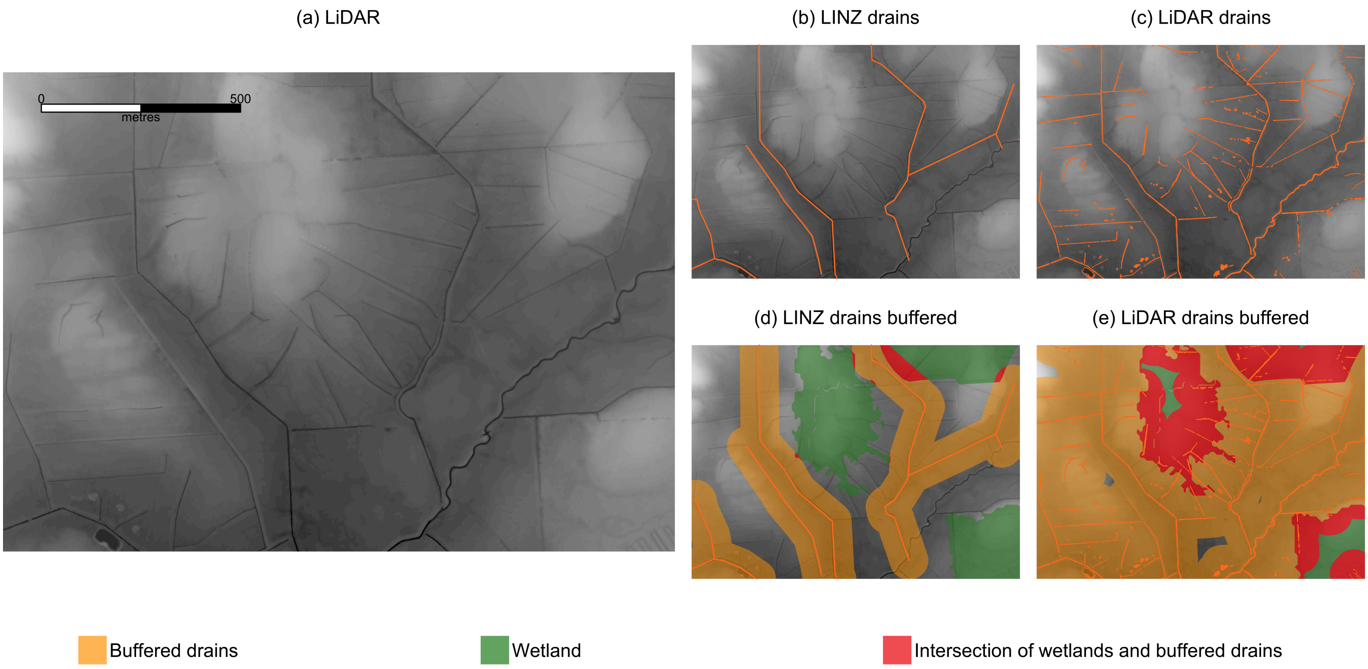

Figure 4. Example 2: (a) LiDAR image, which is the base image in all other panels; b) LINZ drain coverage, clearly showing many drains missing; (c) LiDAR drain coverage with some drains missing, but also a river channel mapped as a drain; (d) LINZ drain coverage buffered by 100 m, showing a small overlap between drains and wetlands; (e) LiDAR drain coverage buffered by 100 m, showing substantial overlap (red) between areas mapped as wetland by FENZ, and the buffered drains. Note little wetland left in green (i.e. not within 100 m of a drain) in this image. Centre of this image is NZTM easting 1266757, NZTM northing 4837570; the waterway shown is Carran Creek.

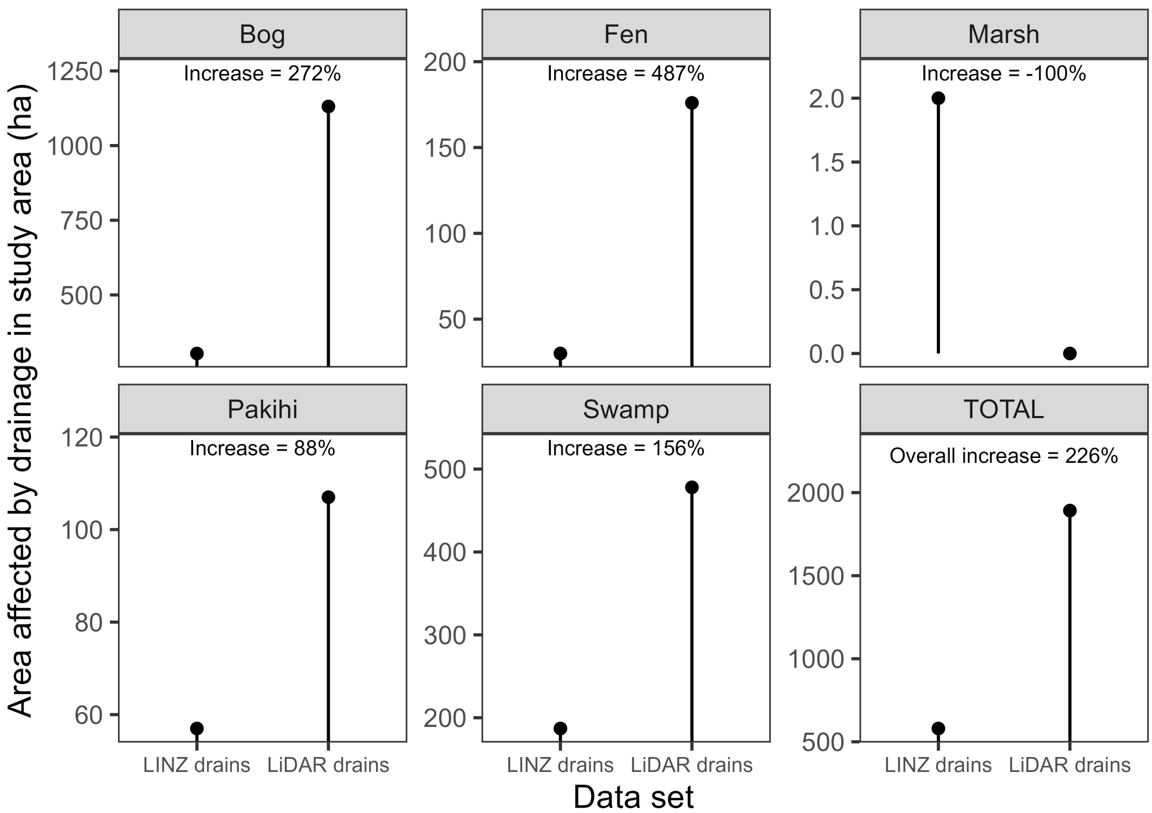

Figure 5. Areal extent of wetland affected by drains, using a 100 m buffer distance, and two different data sets of drain extent. In-panel text indicates the percentage increase by shifting from the national data set (LINZ drains) to the LiDAR derived data set (LiDAR drains). For example, the area of bog increased from 304 ha to 1131 ha, thus 100 × (1131−304) / 304 gives c. 272%, or a more than tripling of the total area. Note y-scale differs across panels and the absolute decrease in marsh detected is small (from 2 ha to 0 ha).

was 62.5% (± 3.34), which is to say that of the total area of drains mapped by the model, 62% (3.91 ha of the total 6.3 ha) was falsely mapped by the LiDAR model. Overall omission and overall commission use different denominators to overall agreement, and to each other (see methods), which is why they may not immediately appear as consistent outputs.

Following this localised validation assessment, we intersected both the manually digitised and LiDAR model with the FENZ wetlands layer across the Waituna catchment, after buffering both by 100 m. This allowed us to assess the effect of the omissions and commissions at a catchment scale on the variable of interest, which is area of wetland within a zone of potential drainage effect. We found very similar results: 88.4 ha of wetlands within 100 m of a drain when using the LiDAR modelled drains, and 90.8 ha of wetlands within 100 m of a drain when using the manually digitised drains. This similarity in area of wetland provides confidence in the accuracy of our increased estimates of wetlands affected by drains within the case study area, derived by the LiDAR model, compared to those derived from the LINZ drains layer.

Visual inspection of the validation model outputs indicated that a major cause of drain omission (false negative) was shallow (potentially older) drains; these drains were easily visible to the human eye using aerial imagery; a less important but still noticeable cause of false negatives was areas of vegetation obscuring, from the point of view of the model, the drain. Conversely, commissions (false positives) were noted to occur most commonly in small streams which may well be deepened/straightened for drainage purposes. As such, the commission is less concerning than it might otherwise be.

Discussion

We have shown there is a substantial area of wetland that is within 100 m of an existing drain when using the LINZ drains layer dataset. For example, 7% of bogs and 4% of swamps by area are within 100 m of a mapped drain at the national scale. This includes 2204 ha of peat bog (7% of New Zealand's total) and 1532 ha of swamp peatland (8% of New Zealand's total). To the extent these peatland areas are affected by drains, these will contribute directly to anthropogenic greenhouse gas emissions via emissions being created as peat decomposes (Leifeld et al. 2019).

We highlight important limitations of the current LINZ drains layer, insofar as calculating drainage near wetlands. The use of the LINZ drains layer for the purpose of calculating drainage near wetlands is likely to be beyond the scope of the what the layer was developed for; however, it is the only layer available at the national scale at present. Given the increased density of drains we found in our case study using LiDAR, a more than tripling of area of wetland near drains, New Zealand's current estimates of the national extent of wetlands under pressure from drainage are clearly underestimated and urgent work is needed to accurately assess the area of wetlands at risk from drainage. This may include both more accurate mapping of drains using a variety of approaches (e.g. ground mapping, aerial mapping, existing records, and LiDAR); but also assessment of the key factors driving distance decay of drainage effects in the New Zealand context.

Extent of underestimate of drains near wetlands

The current wetland extent layer is explicit about not delineating small wetlands (< 0.5 ha), many of which are reported to exist (Dymond et al. 2021) and are disproportionately important for supporting rare and threatened plant species (see Richardson et al. 2015). This means we have likely underestimated the area of wetlands near mapped drains by undercounting affected small wetlands. Additional sources of under-estimation come from the LiDAR layer not being expected to pick up underground drains (e.g. 'tile' or 'mole' drains), which are extensive in some regions. For example, in Southland underground drains are widespread; Pearson (2015) estimates artificial subsurface drainage systems cover 75% of agricultural land in Southland, and artificial subsurface drainage around Awarua wetland, i.e. in the Waituna lagoon catchment was estimated to be "very high: in places (Fig. 5; Pearson 2015). Overall, we consider our estimates to be conservative and likely an underestimate of combined above- and below-ground drainage pressures, but nonetheless, provide new data on the extent of drain impacts upon which further work can be undertaken to assess subsurface drains. Importantly, revealing the areas of wetlands potentially affected by drainage provides critical data to help inform management options for rewetting New Zealand wetlands. The benefits of wetland restoration include reducing greenhouse gas emissions from drained peatlands.

Choice of distance-from-drain

We chose 100 m and 50 m as the widths by which to buffer drains in this analysis to calculate area of impact. This was based on existing work on peat subsidence, ecological changes, and to reflect new regulatory changes which restrict drainage within 100 m of wetlands (see Methods). We highlight that the actual effect of a drain (and distance decay of such effects) will depend on multiple factors including time since drain creation, drain depth, slope, soil type and associated hydraulic properties, and drain width (Luscombe et al. 2016). Our estimates based on the 100 m distance may well be overly conservative in some settings and for some indicators, while being overly liberal in others. This highlights the need for field-verified assessment of extent of drainage effects on wetlands, and identification of key correlating factors for the New Zealand context.

Improvements to LiDAR dataset

Compared with our sample of manually digitised drains, LiDAR drain accuracy was good when compared with the total study area (high overall agreement), and when comparing area of wetland near LiDAR-modelled drains and manually digitised drains, but could be improved. Developing a set of training and testing data points from on-the-ground measures would be the first and likely most important step to improve the model performance.

Conversely, some river channels were identified as drains which is probably topographically correct but arguably incorrect for the purposes of an assessment of artificial drainage. Most of these issues could be resolved using a bigger training/testing dataset and potentially some mask layers, such as river polygons at an appropriate spatial scale. On the other hand, we note many rivers and streams within the catchment have been straightened and maintained for the purposes of efficient drainage, and therefore although not originating as drains, are providing more drainage than would naturally be the case, e.g. Environment Southland (2022) shows multiple rivers and streams functioning as council maintained drains. Further refinement of our model would be required before use as a method to be implemented nation-wide; despite this, we consider it an improvement over existing mapping.

Finally, we note that our manually digitised dataset was created by an operator skilled at digitising and identifying spatial features, but in some areas, particularly with vegetation, or as with the case of streams, it was noted to be difficult to make a decision as to whether something was a drain. On-the-ground work would ameliorate this situation.

Future work

Although constructing new drains within 100 m of wetlands in New Zealand is now highly restricted under recent regulations (Resource Management [National Environmental Standards for Freshwater] Regulations 2020), extensive drainage of wetlands is already present. With ongoing loss of wetlands, we consider it a priority to assemble comprehensive maps of wetland extent (wetlands down to 0.05 ha are required to be mapped under the National Policy Statement for Freshwater Management 2020), and to benchmark drain extent. We note that small wetlands are disproportionately important in conserving biodiversity in New Zealand (Richardson et al. 2015), and internationally (Semlitsch & Bodie 1998; Fahrig 2020), and are not currently mapped: the minimum polygon size for the New Zealand Land Cover Database (LCDB; version 5.0), which has the most recent mapping of wetland extent, is nominally 1 ha, compared with FENZ, which is 0.5 ha. LCDB does not distinguish wetlands by type or substrate, unlike the older FENZ data, and thus we were unable to use LCDB for this work. As LCDB has become the most up-to-date, freely available repository of wetland extent, we hope that LCDB might incorporate wetland type, and/or substrate type, in the future. We consider LiDAR to be a promising tool to identify existing drains near wetlands, and ultimately, to develop strategies to help restore the hydrology of degraded wetlands.

Data and availability

The LINZ dataset used for this paper is archived in datastore; the most up-to-date layer will be available from LINZ (https://data.linz.govt.nz/layer/50262-nz-drain-centrelines-topo-150k/). The LiDAR dataset should be requested from Environment Southland (https://www.es.govt.nz/). The wetland layer used in this analysis from FENZ is also archived in datastore, as is the lakes layer used to erase small mis-identified drains from the LiDAR model. See data archived here: https://doi.org/10.7931/f77d-vw23. Code not archived online.

Author contributions

The project was conceptualised by ORB, JMW, and HSR; methods developed by ORB and RP; investigation undertaken by JMB and HAR; analysis and visualisation completed by ORB, validation by RP, and data curation by ORB and RP. Writing of the first draft was completed by OB with reviewing, and editing undertaken by RB, JMW, JMB, and HAR. The project was supervised and administered by ORB and JMW.

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Supplementary material

Additional supporting information may be found in the supplementary material file for this article:

Appendix S1. LiDAR drain modelling methodology.

Appendix S2. Covariate layers used in the preliminary LiDAR evaluation of the case study catchment.

Appendix S3. Validation circles (numbered in bold above each panel) adjacent to the same area shown with LiDAR.

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