Nutrient load histories for Haldane Estuary and Jacobs River Estuary

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Prepared by:
Bruce Dudley, Arman Haddadchi, Ude Shankar, Rachel Hale

For any information regarding this report please contact:

Bruce Dudley
Hydrologist
Hydrodynamics
+64 3 341 2842
bruce.dudley@ niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 8602
Riccarton
Christchurch 8440

Phone +64 3 348 8987

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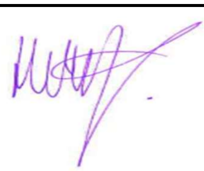	Formatting checked by:	Rachel Wright
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Contents

Tables

Figures

Executive summary

This study examined long-term trends in nutrient loads to Southland's Jacobs River and Haldane estuaries from 1840 to the present. We reconstructed historical land use in each estuary's catchment using a series of land cover maps and used these data to estimate nutrient loads with the CLUES model. By calibrating the model outputs with observed nutrient and flow data, we produced refined time series of nitrogen (N) and phosphorus (P) loads and identified the key drivers behind their changes over time. The results contribute to a stronger scientific understanding of how stressors on Southland estuaries have changed over time.

Nutrient loads to these two estuaries have risen substantially since 1840, with the most pronounced increases occurring after 1950 in response to intensified land use. In Jacobs River Estuary, total nitrogen loads increased from 340 tonnes per year to over 1,200 tonnes per year by 2020. This pattern closely reflects shifts in land use, particularly the conversion of native vegetation to pasture and the expansion of dairy farming and high-density grazing systems.

In contrast, land use in the Haldane Estuary has been relatively stable since the early 2000s. Variations in nutrient loads are more likely attributable to changes in hydrological conditions than to recent alterations in land management. Interestingly, observed nutrient loads to Haldane Estuary were several times higher than those predicted by the CLUES model, suggesting the influence of local hydrology or unaccounted nutrient sources.

By calibrating CLUES model outputs with observed flow and nutrient data, we refined our understanding of nutrient load trajectories. This process revealed that flow variability, uncaptured by the CLUES model alone, is a major driver of fluctuations in nutrient delivery and crucial for accurately estimating recent loading patterns. Whether this hydrologically driven variability leads to measurable ecological impacts remains unclear; future comparisons with biogeochemical indicators in sediment cores may help resolve this.

1 Introduction

Environment Southland (ES) is working to better understand the history of nutrient additions to rivers and estuaries across the Southland Region. This knowledge is vital because land use has changed nutrient and sediment loads to New Zealand estuaries over decadal to centennial timescales, and while estuaries are often grouped by type, each one is unique in its characteristics and vulnerability to these stressors. Some estuaries are more prone to becoming 'unhealthy' due to their sensitivity to excess nutrient and sediment loads. Estuaries are generally most at risk of harmful ecological change when contaminant inputs exceed what the system can tolerate. However, ecological and water quality monitoring of estuaries has typically only begun in recent decades, leaving the original ecological conditions and the relationships between contaminant loads and estuary health poorly understood. By quantifying historical nutrient and sediment loads, and the associated impacts on individual estuaries, ES aims to inform robust water quality targets that support estuary health, enhance amenity value, and uphold the ability to practice mahinga kai. Providing these historical perspectives also helps clarify the whakapapa, or lineage, of an estuary, enabling local iwi and the wider community to engage in meaningful storytelling and culturally appropriate estuary management. Reliable historical information empowers council staff to engage effectively with the Southland community, offering essential context that supports shared understanding and encourages collective ownership of the challenges facing the region's estuaries.

This report addresses the issue of nutrient-driven degradation in Southland's estuaries by quantifying historical changes in nutrient loading over decadal to centennial timescales. The aim is to establish reference 'starting points' for nutrient inputs to individual estuaries and to trace the trajectories of nutrient load changes over time. These historical load patterns will be compared with ecological change time series (in associated work) to better understand how changes in nutrient inputs relate to ecological responses. Together, these datasets can inform the development of scientifically robust and fit-for-purpose nutrient load targets for diffuse-source pollution, supporting efforts to sustain or improve aquatic ecosystem health.

The work presented here focuses specifically on nitrogen (N) and phosphorus (P) loading to two estuaries in Southland: Haldane Estuary and Jacobs River (Aparima) Estuary.

Our general approach involves applying NIWA's CLUES (Catchment Land Use for Environmental Sustainability) model to a series of land use 'snapshots' constructed from historical maps and datasets. The CLUES model is used to estimate nutrient loads for each snapshot, which are then calibrated using observed nutrient load data from recent years. Regression between the calibrated snapshots and land use metrics produces continuous time series of estimated nutrient (N and P) loads entering each estuary.

To enable this modelling, the project began with the collation of historical data, including land cover maps, livestock numbers, fertiliser application rates, point source discharges (such as sewage and agricultural or industrial effluent), and human population data. In addition, historical freshwater flow and nutrient concentration records were assembled to support both the model runs and the calibration process. Some of these data sources have been previously compiled by NIWA and Environment Southland.

2 Methods

2.1 Land use layer preparation and nutrient load modelling

Nitrogen and phosphorus loads to the Jacobs River Estuary and Haldane Estuary between 1840 and 2020 were calculated using the Catchment Land Use for Environmental Sustainability (CLUES) model (Elliott et al. 2016). CLUES estimates annual riverine loads of total nitrogen (TN) and total phosphorus (TP) based on land use across sub-catchments. The model incorporates 19 land use classes representing major rural enterprises, native and exotic forest, and urban areas. Nutrient load predictions are generated through a regression model that combines land use data with information on livestock numbers, catchment characteristics, rainfall, and mean river flows.

Land use input data were developed by generating maps of land cover and slope for key time periods. For the year 1840, land use was derived from the potential vegetation layers of Leathwick et al. (2012), which were based on earlier work by Leathwick (2001) and Leathwick et al. (2003). Land use for 1935 was obtained by digitising historical land use maps. For the period from 1978 to 2020, Land Cover Database (LCDB) maps – ranging from LCDB1 to LCDB5 and the New Zealand Land Resources Inventory (NZLRI) for the 1978 and 2000 years – were used in combination with Agribase farm property data (AsureQuality 2008) to refine land use classification.

CLUES modelling for Haldane Estuary in 2000 was based on LCDB1 covering land cover/land-use between 1996-97, and the NZLRI for slope and land class. The combined information was used to ascertain the types of land use and its attribution to different farming practices, in a coarse form. However, in the latter years (2002 onwards) we had Agribase data that helped us to improve land use classifications with more accurate assignment of farm types and animals, leading to better estimates of nutrient losses. Catchment slope data were sourced from the Land Environments of New Zealand (LENZ) dataset (Leathwick et al. 2002).

Agribase and LENZ were used to disaggregate LCDB grassland classes into specific pastoral land uses associated with different contaminant yields, such as dairy, deer, and sheep and beef farming. The sheep and beef category was further subdivided into lowland intensive, hill country, and high-country systems, reflecting their distinct management practices and associated nutrient losses. Where land within catchments was used for cropping, additional land use classes (including cropland, orchards, and perennial crops) were further subdivided into specific crop types. Remaining LCDB classes, such as native and exotic forests, scrub, tussock, urban areas, rivers, and water bodies, were mapped directly without further subdivision. Stock numbers were obtained from Agribase and aggregated as needed, for example combining sheep and beef into a single class for some purposes. All land use maps were clipped to the boundaries of the Jacobs River Estuary and Haldane Estuary catchments, then imported into the CLUES GIS application and run as distinct scenarios to predict nutrient loads. Where appropriate, some land use classifications were re-grouped in the final outputs to enhance the clarity of plotted results.

The CLUES model incorporates two key metrics to scale expected nutrient losses from pastoral land cover classes: a proportional adjustment for stock density and a proportional adjustment for land use intensity, both relative to a 2008 baseline used in the model's development (Elliott et al. 2016). Stock density for Sheep and Beef, Dairy, and Deer land cover classes was calculated using relationships between stock numbers (or stock unit equivalents, in the case of Sheep and Beef) and land cover area for the wider Southland Region. Adjustments for land use intensity for the Sheep and Beef and Deer classes were based on annual excretal nitrogen (N) loads from the New Zealand Greenhouse

Gas Inventory 1990–2019 (Ministry for the Environment 2021), with values prior to 1990 assumed to be equivalent to those in 1990. For Dairy land use, land use intensity adjustments through time (as opposed to changing land use) were based on milk solids production per cow, using relationships between milk solids output and nutrient inputs per cow on dairy farmland (Luo and Ledgard 2021).

2.2 Loads from point sources

There was one known point source of total nitrogen (TN) and total phosphorus (TP) directly to river water within the Jacobs River Estuary catchment, as well as another notable discharge of wastewater to land. Due to a lack of measured nitrogen and phosphorus discharge data from wastewater treatment plants at Ōtautau (which discharges to land) and Nightcaps (which discharges to the Wairio Stream in the northern Aparima catchment), we estimated nutrient loads from human sources using the method of Robertson and Stevens (2013). This method assumes human-derived wastewater contributions of 2.7 kg of nitrogen and 1.0 kg of phosphorus per person per year. To estimate historical human waste additions to rivers, we summed the 2018 populations of the Ōtautau and Ōhai-Nightcaps census areas and scaled these using historical population trends for the wider Southland region. For the larger Jacobs River Estuary catchment, the total estimated nitrogen and phosphorus loads from human sources were modelled as a point discharge at the location of the Nightcaps wastewater treatment plant. No registered point source discharges exist in the Haldane Estuary catchment, and the human population in the broader Wyndham–Catlins census area is very low (approximately 600 people). As such, human wastewater contributions to nutrient loads in the Haldane Estuary were considered negligible.

2.3 Model calibration

Annual TN and TP data from five river monitoring sites upstream of the Jacobs River Estuary, and a single site upstream of the Haldane Estuary were used to calibrate CLUES model outputs against observed data. Observational data were provided by science staff at ES, who maintain records of daily river flows and monthly nutrient concentrations. The monitoring sites used to calibrate model results for the Jacobs River Estuary were: Aparima River at Dunrobin, Cascade Stream at Pourakino Valley Road, Pourakino River at Traill Road, Opouriki Stream at Tweedie Road, and Aparima River at Thornbury (panel A). For the Haldane Estuary, the single calibration site was Waikopikopiko Stream at Haldane Curio Bay, which represents the major river inflow (panel B).

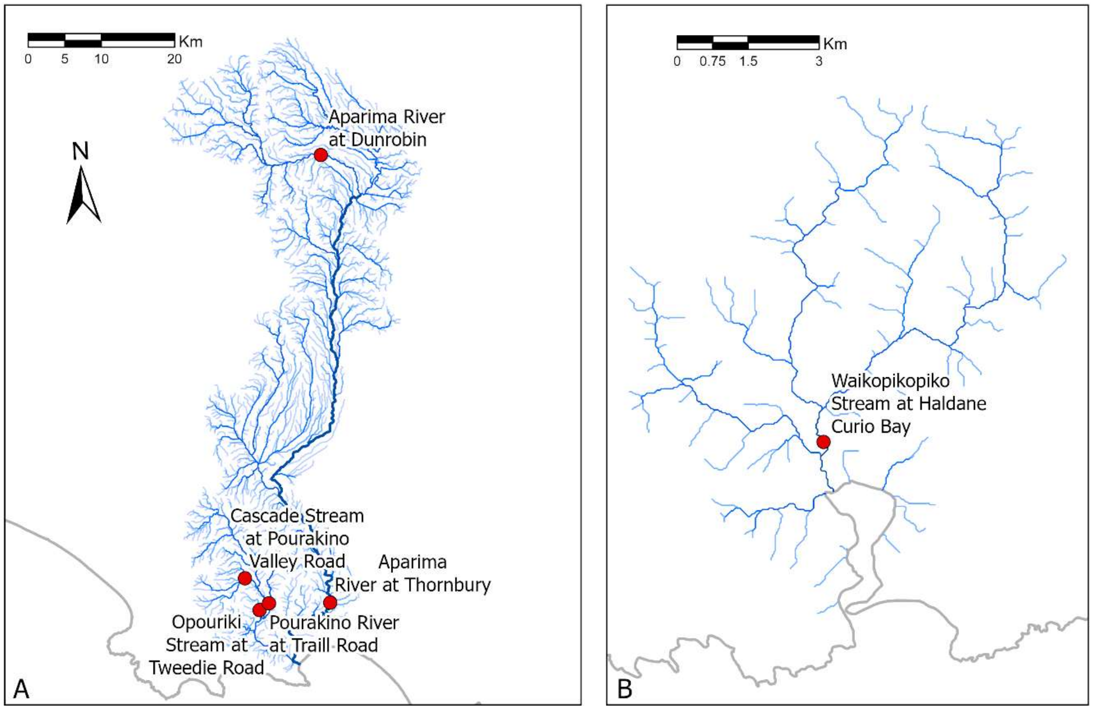

Figure 2-1: Monitoring sites used to calibrate nutrient load models for Jacobs River Estuary (Panel A) and Haldane Estuary (Panel B). Different coloured stream reaches show different stream orders, with lower stream orders represented by lighter blues.

At each site, rating relationships were developed by regressing nutrient concentrations (TN and TP) against concurrent flow measurements. We did this because we wanted to calculate an 'observed' TN and TP annual load, in order to calibrate CLUES model results using those observed at the monitoring sites. These regression models were then applied to continuous flow time series to estimate daily nutrient concentrations, from which annual loads (in tonnes per year) were calculated. We note that even with this approach, uncertainties remain due to the potential influence of hysteresis effects on flow-concentrations relationships; these effects are unlikely to be well-characterised with the monthly sampling datasets available for this study.

The R-squared values from the power regression relationships using flow as the predictor variable for TN at the monitoring sites within the upstream catchments of Jacobs River Estuary ranged from 0.26 for the Aparima River at Thornbury to 0.59 for the Opouriki Stream at Tweedie Road. For the relationship between flow and total phosphorus (TP), R-squared values ranged from 0.33 for the Pourakino River at Traill Road to 0.87 for the Aparima River at Dunrobin.

At the monitoring site upstream of the Haldane Estuary (Waikopikopiko Stream at Haldane Curio Bay), the R-squared value was 0.40 for the regression of TN on flow, and 0.45 for the regression of TP on flow. Further details, including regression coefficients and R-squared values for each site, are provided in Table A-1 in Appendix A.

These observed annual loads were compared with CLUES model predictions for corresponding years. Linear regressions were used to compare observed and modelled loads, allowing calibration of CLUES model outputs to observed nutrient dynamics.

For the Jacobs River Estuary, separate calibration relationships were developed for each of the major contributing rivers, and modelled nutrient loads in terminal reaches were calibrated accordingly.

Comparison of observed total nitrogen (TN) loads with CLUES model estimates shows a root mean squared error (RMSE) of 142 tonnes for the Aparima Branch, 26.3 tonnes for the Pourakino Branch, and 18 tonnes for the Haldane Estuary. For total phosphorus (TP), the RMSE was 7.8 tonnes for the Aparima Branch, 3.7 tonnes for the Pourakino Branch, and 0.36 tonnes for the Haldane Estuary. Calibration coefficients and error values for each site are provided in Table A-2 in Appendix A.

Final annual TN and TP loads to the estuary were calculated by summing calibrated loads for all river reaches discharging into the estuary.

For years lacking land use maps between 1840 and 2020, regression models were used to estimate TN and TP loads, and we note that these regressions also provide estimates for years with maps. We include both regression estimates (black lines) and calibrated CLUES estimates (bars) in Figures 3-1 to 3-3. In the case of Jacobs River Estuary, the best predictors of TN loads in regressions were total stock excreta N loads for the Southland region (2000–2008), and dairy-specific excreta N loads (2009–2020). Due to the strong correlation between TN and TP loads, the same predictors were used in regressions for TP, with modified coefficients. For the Haldane Estuary, total stock excreta N was the best predictor for both TN and TP across the entire time series. Excreta data were obtained from the Ministry for the Environment (2021), and stock numbers were sourced from Statistics New Zealand.

3 Results and Discussion

3.1 Nutrient Loads to estuaries have increased through time

Nutrient loads to both the Jacobs River and Haldane estuaries have increased markedly from pre-European times to the present, consistent with intensifying land use and agricultural development in the Southland region. Nitrogen (TN) and phosphorus (TP) loads calibrated using observational data (Table 3-1) show long-term upward trends, particularly from the mid-20th century onward.

Time series of nutrient inputs (Figure 3-1 to 3-3 and Appendix B) suggest that these increases were not linear. Rather, periods of land use intensification — especially post-1950 — correspond to sharp rises in nutrient inputs. CLUES model estimates (Appendix C), which use land use as the main driver, also reflect this general trend of increasing loads.

While CLUES estimates do not capture annual hydrological variability, the CLUES model does reflect major shifts in land cover and land management that drive long-term nutrient export trends (Plew et al. 2020; Stevens et al. 2022) in Southland estuaries. Despite its limitations, the model remains a useful tool for assessing landscape-level change and identifying critical periods of increase.

Table 3-1: Calibrated loads of nitrogen and phosphorus to Jacobs River and Haldane estuaries through time based on land use maps. Shown are total nitrogen (TN) and total phosphorus (TP), the sum of calibrated N and P loads from all terminal river reaches entering the estuaries.

Year	Nitrogen load Jacobs River Estuary ($t\ y^{-1}$)	Phosphorus load Jacobs River Estuary ($t\ y^{-1}$)	Nitrogen load Haldane Estuary ($t\ y^{-1}$)	Phosphorus load Haldane Estuary ($t\ y^{-1}$)
1840	340	21	35	3
1935	488	26	83	7
1978	787	31	123	5
2000	834	36	221	9
2002	859	38	253	12
2008	964	34	196	12
2012	992	33	188	12
2020	1221	37	137	10

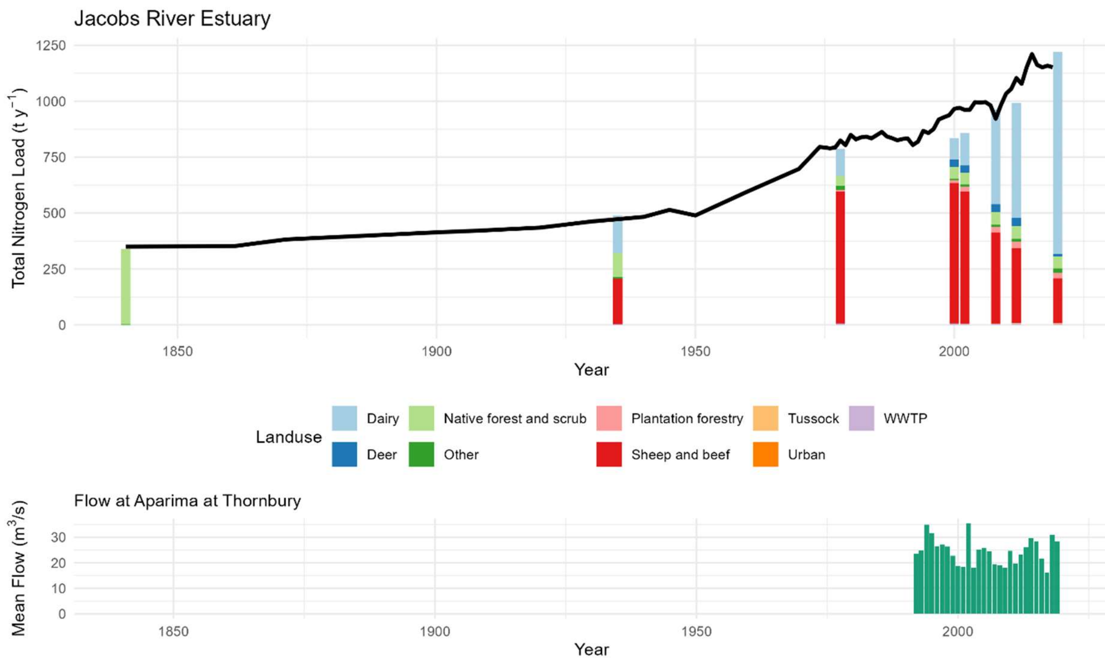

Figure 3-1: Time series of total nitrogen (TN) loads to Jacobs River Estuary since 1840. Bars in the upper plot give loads and proportional contributions of land use categories for years with available land use maps. Black lines show estimated load time series. The lower plot gives mean annual flow for each year flow data is available at the 'Aparima River at Thornbury' flow station.

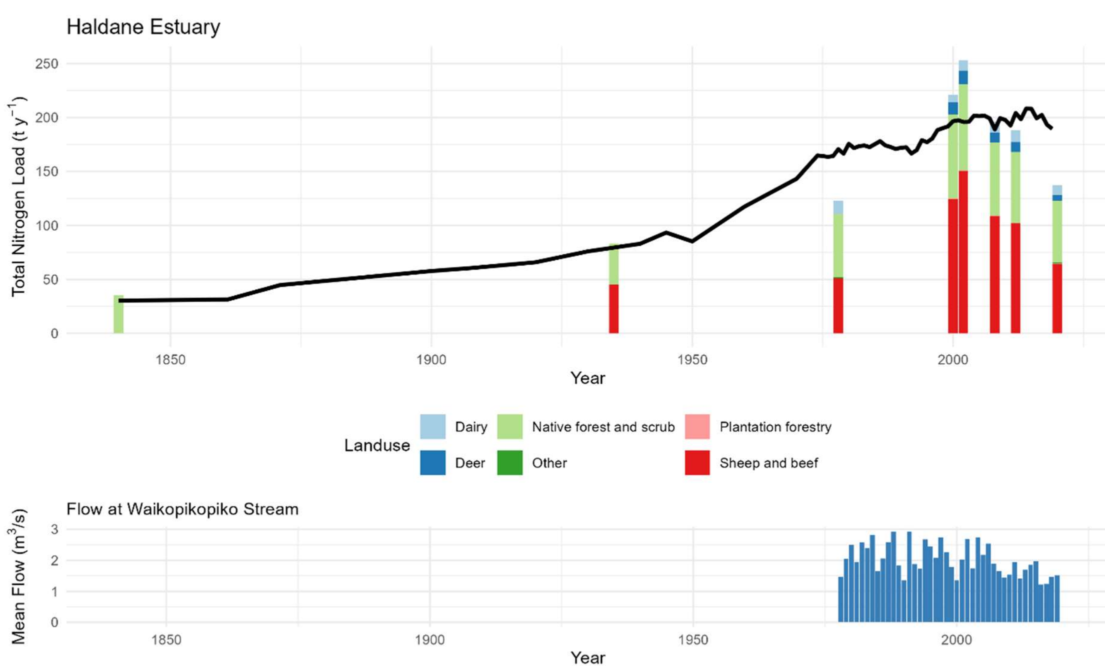

Figure 3-2: Time series of total nitrogen (TN) loads to Haldane Estuary since 1840. Bars give loads and proportional contributions of land use categories for years with available land use maps. Black lines show

estimated load time series. The lower plot gives mean flow for each year flow data is available at the 'Waikopikopiko Stream' flow station.

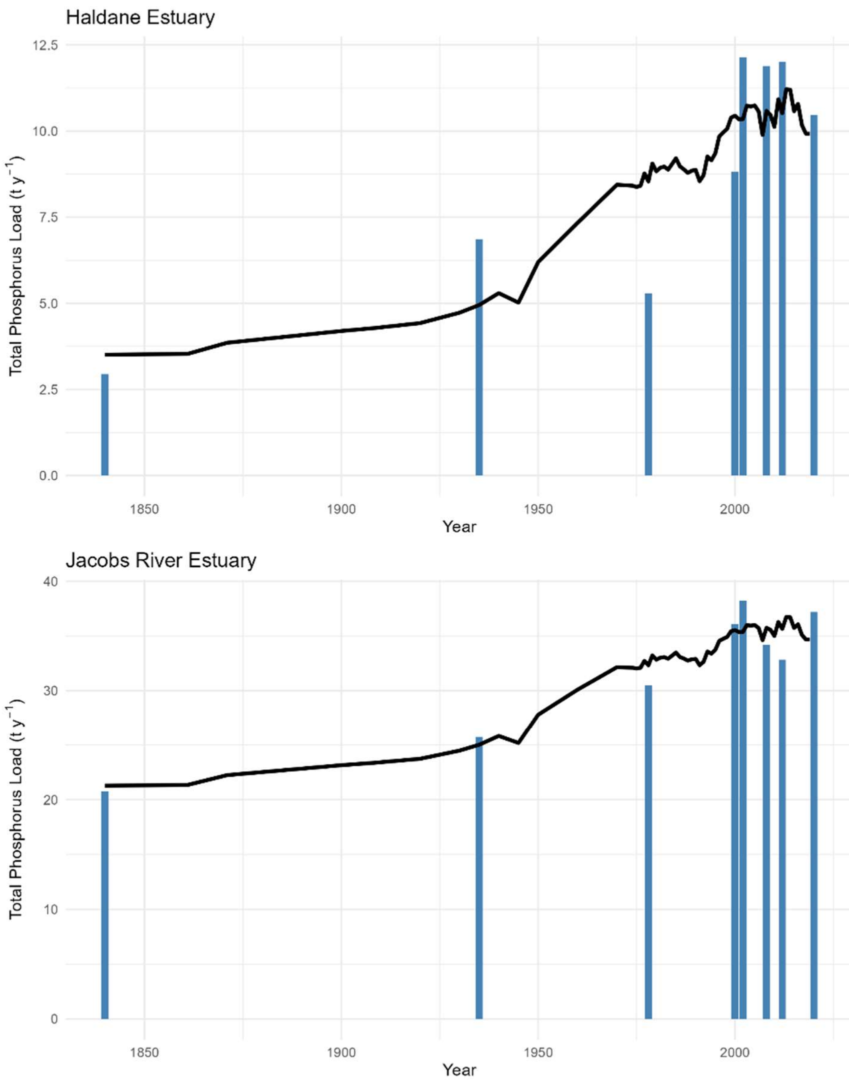

Figure 3-3: Time series of total phosphorus (TP) loads to Jacobs River Estuary and Haldane Estuary since 1840. Bars give loads from years with available land use maps. Black lines show estimated load time series.

3.2 Land use change drove nutrient load increases

Land use change had a much more pronounced effect on nutrient loads to the Jacobs River Estuary than the Haldane Estuary. In Jacobs River Estuary, intensification of pastoral farming, particularly expansion of dairy and high-stock-density sheep and beef systems, influenced load trajectories in the early part of the 21st century – see Figures 3-1 to 3-3. Calibrated TN loads for Jacobs River Estuary show clear increases associated with the shift from native forests and scrub to more intensive grassland systems. Land cover classes such as dairy, deer, and lowland-intensive sheep and beef farming contributed substantially to the rising trend in nitrogen loads.

In contrast, proportional contributions of the major land use / land cover categories in the Haldane estuary catchment have remained relatively unchanged since the start of the 21st century, and with a decline in sheep and beef land use, and in mean flow. Fluctuations in loads in Haldane estuary within this period appeared dependent on hydrological regime. It was notable that calibrated nutrient loads to Haldane Estuary were several times higher than predicted by CLUES, and this discrepancy may be due to local hydrology or unmodelled nutrient sources rather than major land use changes.

3.3 Calibration refined understanding of load trajectories

Calibration of CLUES model output using measured river nutrient loads significantly altered our understanding of nutrient input trajectories, especially for recent decades. For example, high-flow events, which are not captured by the CLUES model, proved to be key drivers of interannual variation in observed loads. These are evident in the differences between 'map years' and estimated trends (Figure 3-1 to Figure 3-3).

By calibrating model results using observed data, particularly from flow-nutrient rating curves, we were able to capture event-driven inter-annual variability and better reflect differences in loading to estuaries. This was especially important in Haldane estuary, where CLUES underpredicted TN and TP loads by factors of four to five in some years.

These findings suggest that interannual hydrological variability can affect nutrient delivery to estuaries, and that ecological impacts may be driven by both chronic nutrient enrichment and episodic high-load events. Biogeochemical indices of ecological condition (e.g., see Hale et al. 2024) in dated sediment cores from these estuaries could help distinguish whether ecological degradation is more closely linked to long-term trends in land use or to more variable, high-magnitude loading events.

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5 Glossary of abbreviations and terms

Catchment	The area of land where rainfall collects and drains into a river, lake, or estuary. Also referred to as a watershed.
CLUES	*Catchment Land Use for Environmental Sustainability* – A national-scale model used in New Zealand to estimate nutrient loads (nitrogen and phosphorus) from land use in catchments. It does not account for interannual hydrological variation but reflects long-term trends based on land cover and land management.
Estuary	A coastal water body where freshwater from rivers mixes with saltwater from the sea. Estuaries are sensitive ecosystems that can be impacted by changes in nutrient inputs.
Estuary Health Programme	A monitoring and research initiative by Environment Southland aimed at improving understanding and management of estuarine ecosystems in the region.
Hydrological Variability	Changes in river flow due to factors such as rainfall and runoff. These variations can significantly influence the transport of nutrients from land to estuaries.
Land Use Intensification	The process of increasing productivity per unit area, often through practices like increased stocking rates, fertiliser application, and irrigation. This often results in higher nutrient runoff.
Load	In this context, "load" refers to the total mass of a contaminant (e.g., nitrogen or phosphorus) transported to an estuary over a given time period, usually expressed in tonnes per year (t y^{-1}).
Mahinga Kai *(Māori)*	Traditional food-gathering practices, reliant on the natural system that sustains them, including the health of freshwater and estuarine environments.
Pastoral Farming	Agricultural systems focused on livestock grazing (e.g., sheep, beef cattle, dairy cows). Intensification of these systems typically increases nutrient runoff due to fertiliser use and animal waste.
Sediment Core	A sample of layers of sediment collected from the bottom of an estuary or lake. Analysed to reconstruct historical environmental conditions, including nutrient levels.
TN (Total Nitrogen)	The total amount of nitrogen (in all its forms) present in water. Excessive nitrogen can cause ecological degradation in estuaries, including algal blooms and oxygen depletion.
TP (Total Phosphorus)	The total amount of phosphorus in water, including dissolved and particulate forms. Like nitrogen, phosphorus is a key driver of eutrophication in aquatic ecosystems, particularly freshwater systems.

Appendix A Flow versus TN and TP calibration relationships

Table A-1: The R-squared and coefficients for the power regression relationship of the monitoring sites for flow against total nitrogen (TN) and total phosphorus (TP) at Jacobs River and Haldane Estuaries.

Sites	Estuary	TN			TP		
		a	b	R2	a	b	R2
Aparima River at Dunrobin	Jacobs River Estuary	0.051	0.450	0.570	0.002	0.785	0.870
Cascade Stream at Pourakino Valley Road	Jacobs River Estuary	0.177	0.183	0.510	0.009	0.187	0.478
Pourakino River at Traill Road	Jacobs River Estuary	0.224	0.287	0.510	0.010	0.463	0.330
Opouriki Stream at Tweedie Road	Jacobs River Estuary	2.960	0.292	0.590	0.079	0.530	0.760
Aparima River at Thornbury	Jacobs River Estuary	0.350	0.300	0.260	0.005	0.540	0.680
Waikopikopiko Stream at Haldane Curio Bay	Haldane Estuary	0.332	0.211	0.400	0.028	0.283	0.450

Table A-2: Calibration coefficients used to adjust CLUES model estimates for total nitrogen (TN) and total phosphorus (TP).

	TN			TP		
	Intercept (a)	Slope (b)	RMSE (t)	Intercept (a)	Slope (b)	RMSE (t)
Aparima Branch	2.18	0.81	142.02	1.18	0.72	7.77
Pourakino Branch	0.51	1.23	26.32	0.54	1.30	3.67
Haldane	0.00	3.43	18.04	4.97	-2.66	0.36

Appendix B Estimated nutrient load time series data

Table B-1: Time series of total nitrogen (TN) and total phosphorus (TP) loads to Jacobs River (Aparima) Estuary and Haldane Estuary, estimated using regression against stock excreta time series.

Year	Nitrogen load Jacobs River Estuary (t y^{-1})	Phosphorus load Jacobs River Estuary (t y^{-1})	Nitrogen load Haldane Estuary (t y^{-1})	Phosphorus load Haldane Estuary (t y^{-1})
1840	350	21	30	4
1861	352	21	31	4
1871	382	22	45	4
1900	414	23	58	4
1908	421	23	61	4
1920	435	24	66	4
1930	463	24	76	5
1940	483	25	83	5
1945	514	26	93	5
1950	489	25	85	5
1960	596	28	117	6
1970	697	30	143	7
1974	795	32	165	8
1975	793	32	164	8
1976	789	32	164	8
1977	793	32	164	8
1978	824	33	171	9
1979	804	32	167	9
1980	849	33	176	9
1981	830	33	172	9
1982	838	33	173	9
1983	841	33	174	9
1984	834	33	173	9
1985	848	33	175	9
1986	863	33	178	9
1987	842	33	174	9
1988	835	33	173	9
1989	825	33	171	9
1990	831	33	172	9
1991	833	33	172	9
1992	804	32	167	9
1993	820	33	170	9
1994	867	34	179	9
1995	858	33	177	9
1996	875	34	180	9

Year	Nitrogen load Jacobs River Estuary (t y^{-1})	Phosphorus load Jacobs River Estuary (t y^{-1})	Nitrogen load Haldane Estuary (t y^{-1})	Phosphorus load Haldane Estuary (t y^{-1})
1997	918	35	188	10
1998	928	35	190	10
1999	937	35	192	10
2000	966	35	197	10
2001	971	36	197	10
2002	961	35	196	10
2003	962	35	196	10
2004	996	36	202	11
2005	994	36	201	11
2006	996	36	202	11
2007	981	36	199	11
2008	922	35	189	10
2009	982	36	199	11
2010	1034	36	198	10
2011	1055	35	193	10
2012	1104	36	204	11
2013	1077	36	198	11
2014	1153	37	208	11
2015	1210	37	208	11
2016	1162	36	199	11
2017	1151	36	202	11
2018	1159	35	193	10
2019	1152	35	190	10

Appendix C Uncalibrated CLUES nutrient load time series data

Year	Nitrogen load Jacobs River Estuary (t y^{-1})	Phosphorus load Jacobs River Estuary (t y^{-1})	Nitrogen load Haldane Estuary (t y^{-1})	Phosphorus load Haldane Estuary (t y^{-1})
1840	431	40	21	2
1935	683	55	31	3
1978	1177	66	33	3
2000	1183	71	36	3
2002	1199	75	42	4
2008	1376	75	42	4
2012	1426	75	43	4
2020	1856	84	46	4