

## **Abstract**

Glacial debris is a productive source of sediment. Glacial melt resulting in the formation of proglacial lakes is an emergent phenomenon of anthropogenic climate change. Globally, there is a lack of data addressing proglacial lake effects on downstream riverine and lacustrine sedimentation. It is unclear whether proglacial lakes as sediment traps restrict glacial debris in downstream watersheds. This study evaluated *in situ* (2004-2023) river turbidity data and Sentinel-2 satellite imagery lake turbidity data (2016-2024) from three watersheds in New Zealand's Southern Alps, a region in which glacial melt is relatively recent. Sentinel-2 imagery was modeled to return Normalized Difference Turbidity Index (NDTI) values for individual lakes. Statistical trend and regression analysis was evaluated between systems and methods of data collection in order to compare both system behavior and relatedness between rivers and lake turbidity. This study found that watershed turbidity trends and values are not consistent between lakes and rivers. It is possible that due to lakes and rivers responding differently to sedimentation, lakes are poor predictors of whole watershed turbidity, or that NDTI is an inaccurate form of remote sensing measurement. Glacial watersheds with upstream proglacial lakes were found to be less turbid than those without. Glacial watersheds as a whole were found to be far more turbid than non-glacial watersheds, regardless of extenuating anthropogenic factors. Glacial meltwater signals were detected in both glacial watersheds with and without upstream proglacial lakes. These findings demonstrate proglacial lakes to be effective mitigators of glacial sedimentation in comparison to other glacial watersheds, but not to the extent that glacial debris fluctuations can be fully disrupted.

# Examining Proglacial Lake Effects On Downstream Sedimentation In New Zealand's Southern Alps Through Sentinel-2 Turbidity Index

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## 1. Introduction

Glaciers have been globally retreating since the end of the Little Ice Age (LIA) (Marta, Silvio, et al., 2021). With the advent of increased anthropogenic activity affecting world climate conditions, this retreat has only been accelerated (Marzeion, Ben, et al. 2014). The Southern Alps of New Zealand are home to more than 3,100 glaciers exceeding 0.01 km<sup>2</sup>, but these glaciers, too, are advancing towards extinction with every passing year. (Chinn, Trevor J.H. 2000) Despite a period of advancement between ~1983 to 2008, when shifting climatic factors in the South Pacific preserved Southern Alps glaciers with increased rainfall and cooler temperatures, the consequences of manmade climate change have appeared dramatically for New Zealand in the new millennium. Compared to ice coverage volumes during the LIA, the current Southern Alps possess between 41 to 62% less glacial coverage, with retreat expected to continue escalating at increasing rates with each passing year. (Mackintosh, Andrew N., et al. 2017)

The Southern Alps' rapid glacial retreat has resulted in a number of changes to the landscape. Most noticeably, the formation of ice-marginal proglacial lakes at the glacial terminus that fill natural land depressions (overdeepenings) with an influx of glacial meltwater. (Carrivick, Jonathan L., et al. 2022) The inverse relationship between glacial ice mass and proglacial lake volume increase is well-known, and the number of lakes resulting from melting glaciers is only expected to grow globally.

Proglacial lakes, as emerging components of New Zealand's complex hydrological systems, introduce a variety of new factors to the landscape, such as an influx of available water throughout the year, and potential effects on water quality. (Carey, Mark et al. 2017) Glacial debris left behind by retreat is easily transported into the resulting proglacial lakes. (Hart, Jane K. 1996) Debris exposed by deglaciation has the potential to impact water quality in a number of ways, including increased streamflow, altered water chemistry due to exposure to relatively dilute meltwater, interrupted meltwater flux, and impacted weathering and thermal patterns. (Moore, R. D., et al. 2009)

These changes can have negative impacts on local ecosystems, and the drainage basins below the Southern Alps are particularly diverse environments that support dynamic fisheries, fauna, and other coastal/freshwater marine life. (Morrison, Mark Andrew, et al. 2009) This study recognizes these impacts and seeks to identify an additional category of change: increased

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downstream sedimentation through observable turbidity. Sedimentation is a high-impact variable that has been shown to decrease primary productivity, disrupt marine ecosystem habitats, and interfere with biological functions of affected organisms in New Zealand stream systems, making it a variable of interest when concerning the health and preservation of these ecosystems. (Ryan, Paddy A. 1991) Potential impacted species include longfin eels, mudfish, torrentfish, shortjaw kōopu, various sedges/grasses, wetland forest trees/shrubs, and freshwater algae. (Dept. Conservation Te Papa Atawhai)

Research has been conducted on the coast of the Gulf of Alaska, investigating the relationship between glacially-fed watersheds and proglacial lakes. (Vowels, Lily K., et al. 2025) Other similar studies on proglacial lake downstream sedimentation have been conducted in Norway and Austria, among other European locations. (Bogen et. al 2013, Geilhausen, Martin, et al. 2013) Vowels et. al. (2025) noted that the focus on Europe has left large swaths of the world unstudied, which has created an opportunity to expand the study to a more global scope, thereby offering more data on the subject.

Vowels et. al. (2025) determined that rivers downstream of proglacial lakes had less suspended sediment than those without. Despite proglacial lakes being poor statistical predictors of sediment change according to their findings in the Gulf of Alaska, the study urged investigation into how wider watersheds respond to proglacial lakes, following the consensus that proglacial lakes act as sediment traps, disrupting sedimentation further downstream.

From this identifiable gap in the research, there is an opportunity to use the glacially-fed hydrological network of the Southern Alps to aid in providing additional evidence in another quadrant of the world. This study has the motivation of investigating the impact of proglacial sedimentation on the broader hydrological system, both lakes and rivers, as well as providing data to further a deeper understanding of proglacial systems in a wider variety of study locations.

This study aims to examine a number of sites that can be characterized by three categories; i) hydrological systems fed by ice-marginal proglacial lakes, ii) systems fed by glaciers without proglacial lakes, and iii) systems not fed by glaciers. The sites will be divided into several sub-sites that will each be evaluated for their observable turbidity and water quality in order to determine if ice-marginal proglacial lake influence on hydrological systems has a relevant impact on downstream water quality.

Employed techniques to achieve this goal will include an analysis of both proglacial and downstream lake satellite imagery and *in situ* river, stream, and lake water quality data provided by pre-existing datasets assembled by Land, Air, Water Aotearoa (LAWA) and the National Institute of of Water and Atmospheric Research (NIWA), coupled with statistical modelling.

The Southern Alps contribute to vast economically and culturally important hydropower infrastructure, scenic tourism and community land use. (Purdie, Jennifer, 2022) Understanding the influence of proglacial lakes on watershed turbidity and water quality is invaluable as glacial retreat progresses. The techniques employed in this study are applicable to continued global examinations of glacially-fed watershed turbidity, which is encouraged for the purpose of

expanding the development of climate-ready responses to worldwide periglacial landscape evolution.

## 2. Methods

### 2.1 *Site Selection*

The Southern Alps of New Zealand comprise a 500 km-long mountain range that stretches across much of the lower South Island, with the central range being 300 km long and 120 km wide. Glaciers are present in the mountain peaks, covering about 5% of the Alp’s range. (Fitzsimons, Sean J., and Heinz Veit, 2001) The snow and glacial melt of the Southern Alps are drained by steep, dense, high-energy rivers that feed into population centers on either side of the Alp’s ‘Main Divide.’ (Korup, Oliver, Jochen Schmidt, and Mauri J. McSaveney, 2005) Therefore, rivers of differing sources are commonly found close together, and feed into each other as well as stable bodies of water such as lakes, dams, reservoirs, and marshes.

When determining sites that could be used as examples for the three categories outlined in this study (systems fed by ice-marginal proglacial lakes, systems fed by glaciers without ice-marginal lakes, and systems not fed by glaciers); the main criteria consisted of i) proximity to other considered sites ii) amount of stable bodies of water with inflow and/or outflow to the watershed, iii) availability of archival *in situ* data, and iv) cultural/economic significance. Based on these criteria, three watersheds were ultimately selected.

**Table 1.** Study Sites and Their Characteristics By Category

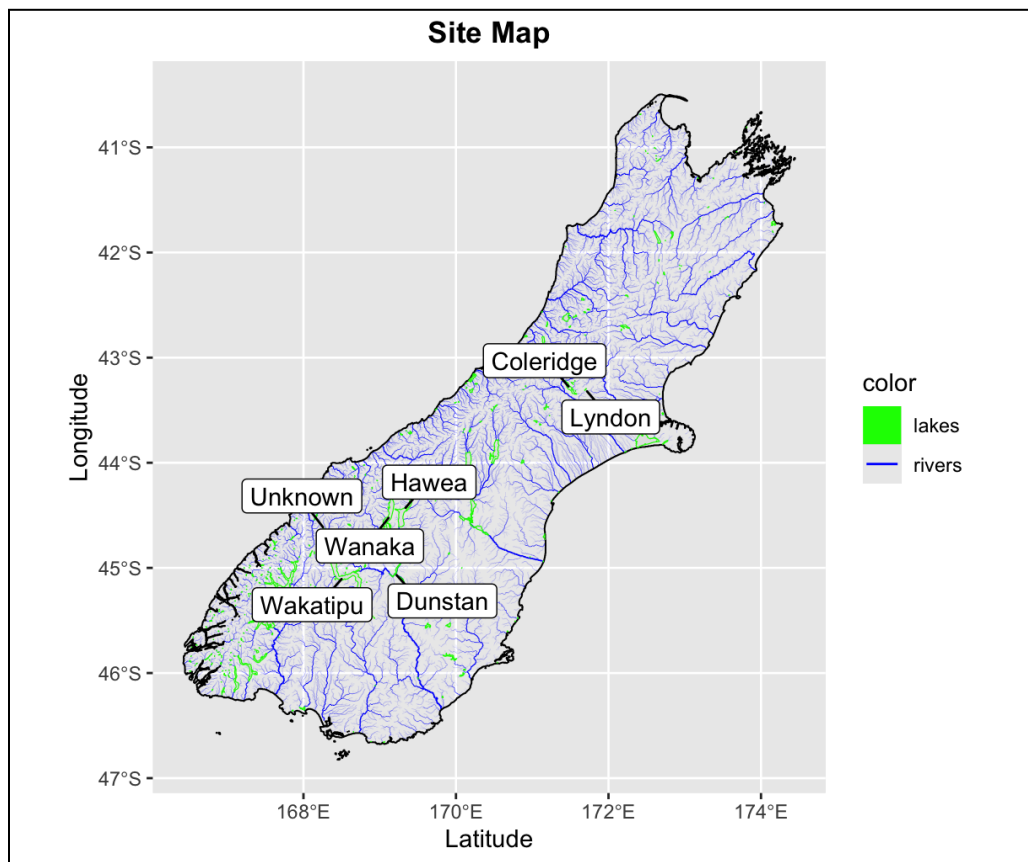
*NGF = Non-Glacially Fed*

*GF = Glacially-Fed*

Site Name	Category	Associated River	River Catchment (km <sup>2</sup> )
Lake Wanaka	NGF	Clutha River	21400 km <sup>2</sup>
Lake Hawea	NGF	Clutha River	21400 km <sup>2</sup>
Lake Dunstan	NGF	Clutha River	21400 km <sup>2</sup>
Lake Unknown	GF + No Lake	Dart River	632 km <sup>2</sup>
Lake Wakatipu	GF + No Lake	Dart River	632 km <sup>2</sup>
Lake Coleridge	GF	Rakaia River	2,900 km <sup>2</sup>
Lake Lyndon	GF	Rakaia River	2,900 km <sup>2</sup>

For the control, a non-glacially fed (NGF) watershed, the Clutha River was selected. Spanning 21400 km<sup>2</sup>, and draining 125 km of the Southern Alps, the Clutha possesses the largest catchment of all rivers in New Zealand. (Murray, D.L, 1975) Several large lakes have inflow and/or outflow into Clutha River; Lake Wanaka (the source of the Clutha), Lake Hawea, and Lake Dunstan, which was formed on the Clutha after the construction of a man-made dam in April 1992 for the purpose of orchard/vineyard irrigation. (Allan, Jonathan C, 1998) Due to the presence of these large lakes, Lake Dunstan's economic/agricultural significance, and the Clutha River being a significant waterway with available *in situ* data in addition to meeting the requirement of an NGF river flowing out of the Southern Alps, the Clutha was determined to be the most viable candidate.

**Fig. 1** Site Map

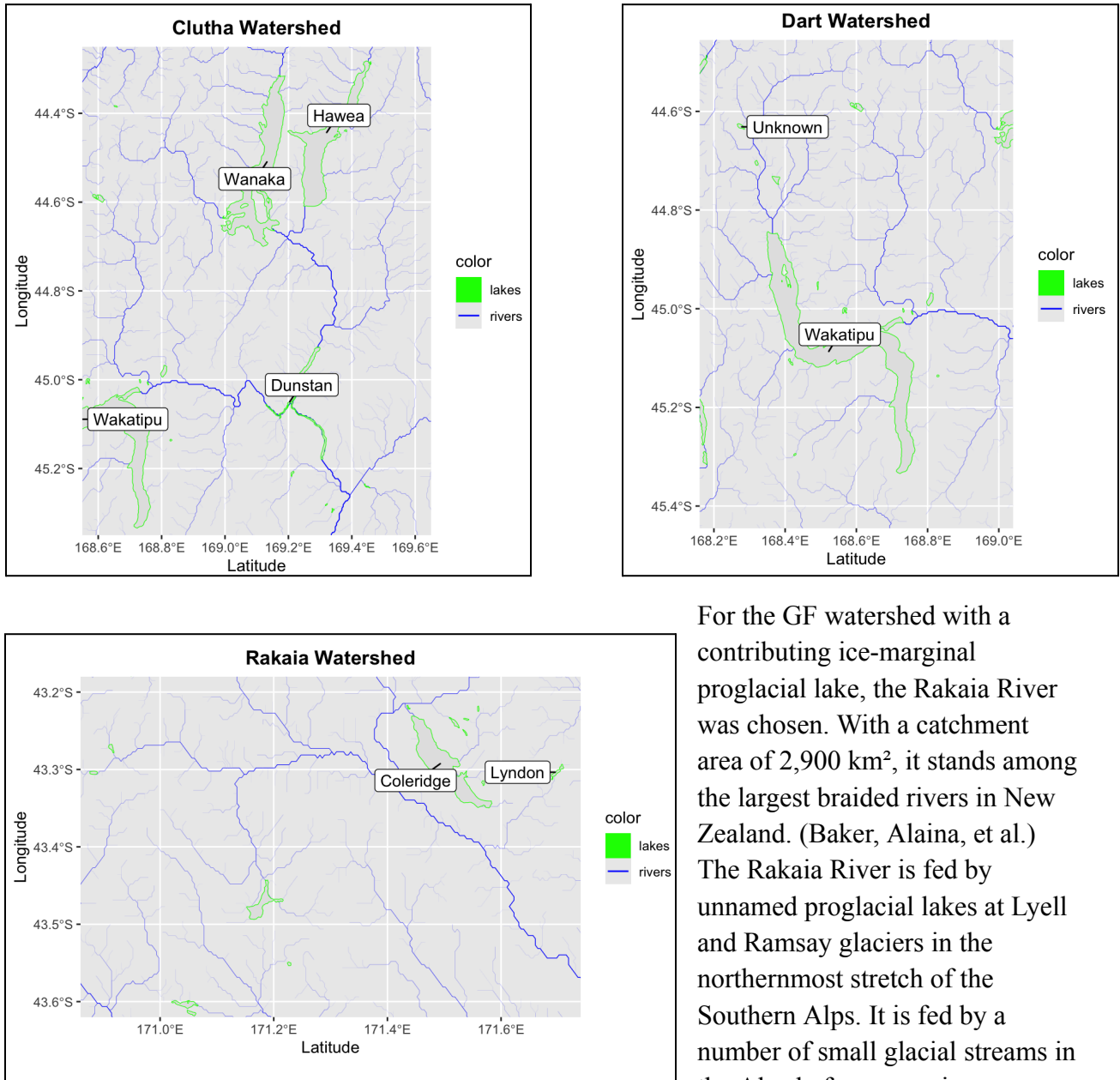


**Fig. 1** Site map using the HydroLAKES, HydroBASINS, and HydroRIVERS databases. The displayed sites include Lake Wanaka, Lake Wakatipu, Lake Dunstan, Lake Hawea, and Lake Coleridge, Lake Lyndon, and Lake Unknown.

For the glacially-fed (GF) watershed without a contributing ice-marginal proglacial lake, the Dart River (Te Awa Whakatipu) was chosen. The Dart River, with its headwaters at Dart Glacier in the Southern Alps, has a 632 km<sup>2</sup> catchment that feeds into Lake Wakatipu, the third-largest lake in New Zealand. (Wild, Michelle, et al. 2008) In addition to Lake Wakatipu,

Dart River also has inflow into Lake Unknown further upstream. Lake Mystery, upstream of Lake Unknown, was also considered, but was ultimately disregarded due to its relatively small size, making it insufficient for satellite image sampling. Dart River was chosen for its inflow into a significantly large lake, its origin in the Southern Alps at a glacier that presently lacks any glacial lake, its proximity to other selected sites, and availability of *in situ* data.

**Fig. 2** Watershed Maps



For the GF watershed with a contributing ice-marginal proglacial lake, the Rakaia River was chosen. With a catchment area of 2,900 km<sup>2</sup>, it stands among the largest braided rivers in New Zealand. (Baker, Alaina, et al.) The Rakaia River is fed by unnamed proglacial lakes at Lyell and Ramsay glaciers in the northernmost stretch of the Southern Alps. It is fed by a number of small glacial streams in the Alps before emerging as a

large high-energy braided river that flows straight into the Atlantic Ocean, ~80 km south of Christchurch. Within its catchment is Lake Coleridge and Lake Lyndon, which are also partially

fed by the glacial river Wilberforce. Lakes Lyndon and Colerdige are not fed by the proglacial lakes. The Rakaia River was chosen for its significant flow contribution by proglacial lakes, large catchment area, and availability of *in situ* data.

## 2.2 Sentinel-2 Imagery

Harmonized Landsat Sentinel-2 S30 (HLSS30) images have 13 spectral bands with 30m spatial resolution and a revisit frequency of 2-3 days. HLSS30 images were downloaded from NASA Earthdata Search. To acquire images with adequate visibility, images were filtered for cloud fraction between 0-45. The temporal constraint on the images was between January 1, 2016 – December 31, 2024; outlining a study period of 9 years. This time period was chosen to ensure that each year of data was complete, per Sentinel-2’s launch date of June 23, 2015. The below table details the Sentinel-2 bands and their definitions.

**Table 2.** Sentinel-2 Multispectral Imagery Band Definitions

Band 1	Coastal/Aerosol
Band 2	Blue
Band 3	Green
Band 4	Red
Band 5	Red Edge-1
Band 6	Red Edge-2
Band 7	Red Edge-3
Band 8	NIR Broad
Band 8a	NIR Narrow
Band 9	Water Vapour
Band 10	SWIR – Cirrus
Band 11	SWIR
Band 12	SWIR

### 2.2.1 Binary Water Mask Using NDWI Values

To identify water in the Sentinel-2 imagery, Bands 3 and 8 of the satellite data were used. The reflectance was first calculated by the Normalized Water Difference Index (NDWI) equation, as given by Mcfeeters (1996), where Red and NIR are designated as Bands 3 and 8, respectively.

$$NDWI = \frac{Red - NIR}{Red + NIR}$$

This is given that water has its highest reflection in the visible region, and absorbs all energy in the NIR region of electromagnetic radiation. (Vaibhav Garg, Shiv Prasad Aggarwal & Prakash Chauhan, 2020) NDWI values range between -1 and +1, with the value of 0 theoretically representing water. In order to represent this, a binary raster was calculated and applied to the NDWI values, which calibrated the resulting image to the NDWI value range, allowing the model to identify appropriate values as '1' and remaining values as 'NA.'

### 2.2.2 Calculating NDTI Values

Following the calculation of NDWI and the creation of the binary raster, Bands 3 and 4 were used in accordance with the strategy developed by Lacaux et al. (2007) to calculate the Normalized Turbidity Index (NDTI) values, where Red and Green are designated as Bands 3 and 4, respectively.

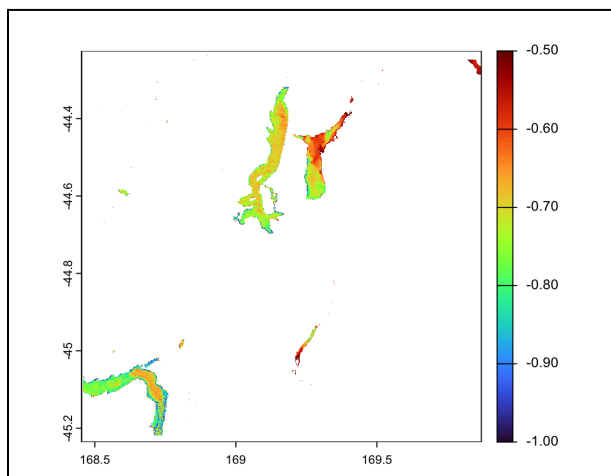
$$NDTI = Red - Green / Red + Green$$

The NDTI values are based on the reflectance of the bands, and correlate to the turbidity of the water in the Sentinel-2 imagery. This is based on the idea that turbid water tends towards higher red wavelength reflectance, while generally pure water tends towards green wavelength reflectance. Therefore, red and green bands were chosen to evaluate the imagery for turbidity values. NDTI values were calibrated between a range of -1 to -0.5 in order to best render values according to cloud coverage. Comparative tests were done to ensure that this range was accurate, however, different ranges may be employed in future studies.

### 2.2.3 Turbidity Using Water Mask and NDTI

The turbidity model was rendered by applying the binary raster onto the NDTI values, creating an image that visually displays turbidity on top of the water mask. In order to properly display the value range, infinite values were removed, and a color scale was applied to visualize the turbidity. The resulting image displays only areas where water is present in the original satellite image, with a color scale corresponding to the turbidity value range on top of the water-present areas.

**Fig. 3** Turbidity Modelling Example



**Fig. 3** A demonstration of the visual result of the turbidity model in RStudio. Pixels display values on a scale of -1 to -0.5, with 256 colors representing values overlaid on the water mask from the original Sentinel-2 image.

### 2.2.4 Applying Lake Polygons

New Zealand lake polygon shapefiles were obtained from the HydroLAKES database. The values from the turbidity visualizations were extracted for each individual lake by projecting the HydroLAKES polygons onto the satellite images and using the R *terra* package ‘extract’ function to align the turbidity values with the polygons. This produced a dataset that contains values for an individual lake from each image.

### 2.2.5 Preparing for Analysis

Extracted values were averaged according to the mean value, which was compiled into datasets sorted by lake. Each lake dataset contains the mean turbidity of an individual satellite image (filtered to only display the values of a single lake in the image), the image ID, and the observation date of that image.

## 2.3 In Situ Data

*In Situ* data was obtained from public water quality data provided by Land, Air, Water, Aotearoa (LAWA), a federal project of the New Zealand government in collaboration with regional/unitary councils, Massey University, and the Tindall Foundation. A portion of the LAWA data was also provided by the National Institute of Water and Atmospheric Research (NIWA), a Crown Research Institute of New Zealand, and the Ministry of the Environment. Turbidity data was measured using Formazin Nephelometric Units (FNU), and collected between 2004-2023, with Dart River starting data collection in 2006.

**Table 2.** River Stats (Excluding Outliers)

Site Name	Clutha	Dart	Rakaia
Mean Turbidity	3.4114	75.6333	38.12908
Median Turbidity	1.50	18.7	4.85
Standard Deviation	5.8675	148.3695	105.6790
Interquartile Range	2.420	66.95	15.725
Mean Absolute Deviation	1.3343	23.12856	5.1149
Min Turbidity Value	0.24	0.30	0.40
Max Turbidity Value	51	1010.0	880.0
Range	50.76	1009.7	879.6

Clutha River data was collected at Luggate Bridge (The Red Bridge), ~20 km southwest downstream of the river’s headwaters at Lake Wanaka, and upstream of Lake Dunstan; Balclutha, a township ~16 km northwest of the river’s mouth in the Pacific Ocean; and Miller’s Flat, a township

~89 km south and downstream of Lake Dunstan. Dart River data was collected at The Hillcocks,

a cluster of small hills of unknown origin in the Dart River floodplain, ~50 km northeast and upstream of Lake Wakatipu, and downstream of Lake Unknown. Rakaia River data was collected at Rakaia River Gorge, ~40 km southwest and downstream of Lake Coleridge; and the State Highway 1 Bridge crossing, ~15 km north of the river’s mouth in the Pacific Ocean.

**Table 3.** River Stats (Including Outliers)

Site Name	Clutha	Dart	Rakaia
Mean Turbidity	3.6548	115.6875	62.8790
Median Turbidity	1.50	19.0	4.95
Standard Deviation	7.3813	395.2287	273.3181
Interquartile Range	2.520	71.70	18.5250
Mean Absolute Deviation	1.3639	23.7216	5.2632
Min Turbidity Value	0.24	0.30	0.40
Max Turbidity Value	88.1	4000.0	3800.0
Range	87.86	3999.63	3799.6

Clutha River data was collected in 681 instances monthly over a period of 19 years, averaging 35.84 instances per year. Dart River data was collected in 161 instances monthly over a period of 17 years, averaging 9.47 instances per year. Rakaia River data was collected in 330 instances monthly over a period of 19 years, averaging 17.36 instances per year.

### 3. Results

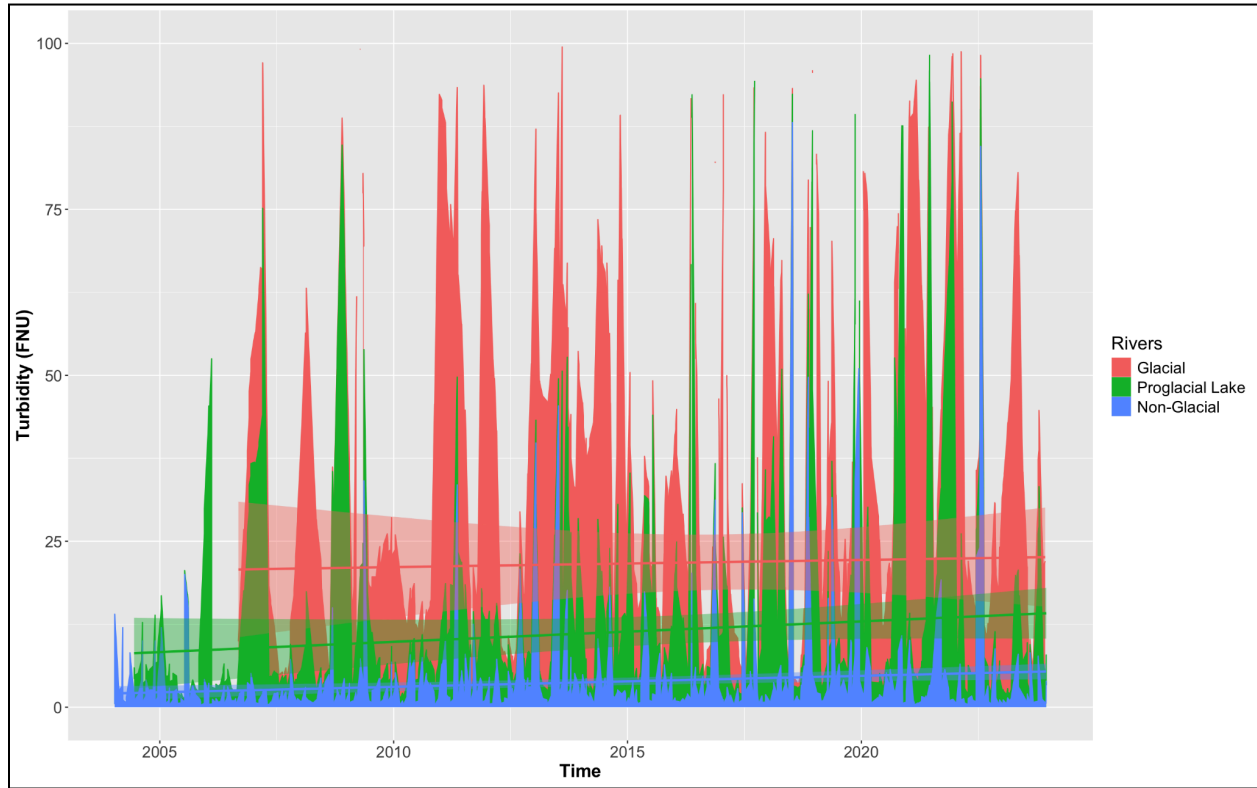
#### 3.1 In Situ Results

Each of the three rivers presents different trends, with some trends associated with sedimentation events. The increase in outlier FNU values in the Dart River data in 2014 can be attributed to a major landslide in the Dart Valley circa January 4, 2014. (Petley, Dave, 2014) However, this landslide did not produce the maximum recorded turbidity value for the Dart River, which was recorded on March 1, 2011 as 4000 FNU. The cause of this extreme value is unknown, and may be inaccurate, but was included in the non-outlier datasets for transparency. Dart River presents with a decreasing trend in turbidity, but still maintains the highest mean value, even when outliers are removed, with a mean value of 115.68 including outliers and 75.63 excluding outliers. This compared to Clutha River (3.65, 3.41) and Rakaia River (38.12).

Rakaia River recorded its highest value of 3800 on January 24, 2019, with several high values also recorded into the 2020s. In December of 2019, and following into 2020, the river experienced mass flooding. These floods resulted in severe damage to the river’s banks and the need for several natural infrastructure projects to restore the integrity of the river and surrounding floodplain. It is possible that this uptick in high values correlates with increased flood events in 2019 and beyond. (Environment Canterbury, 2024)

The rivers that are derived from glacial sources demonstrate much higher turbidity values, with Rakaia and Dart Rivers both recording values over 3000, while Clutha River has a maximum value of only 88.1. Additionally, the glacially-fed rivers' compiled monthly values display larger ranges of turbidity than Clutha River's compiled monthly values (1399.7 and 3799.6, versus 87.86).

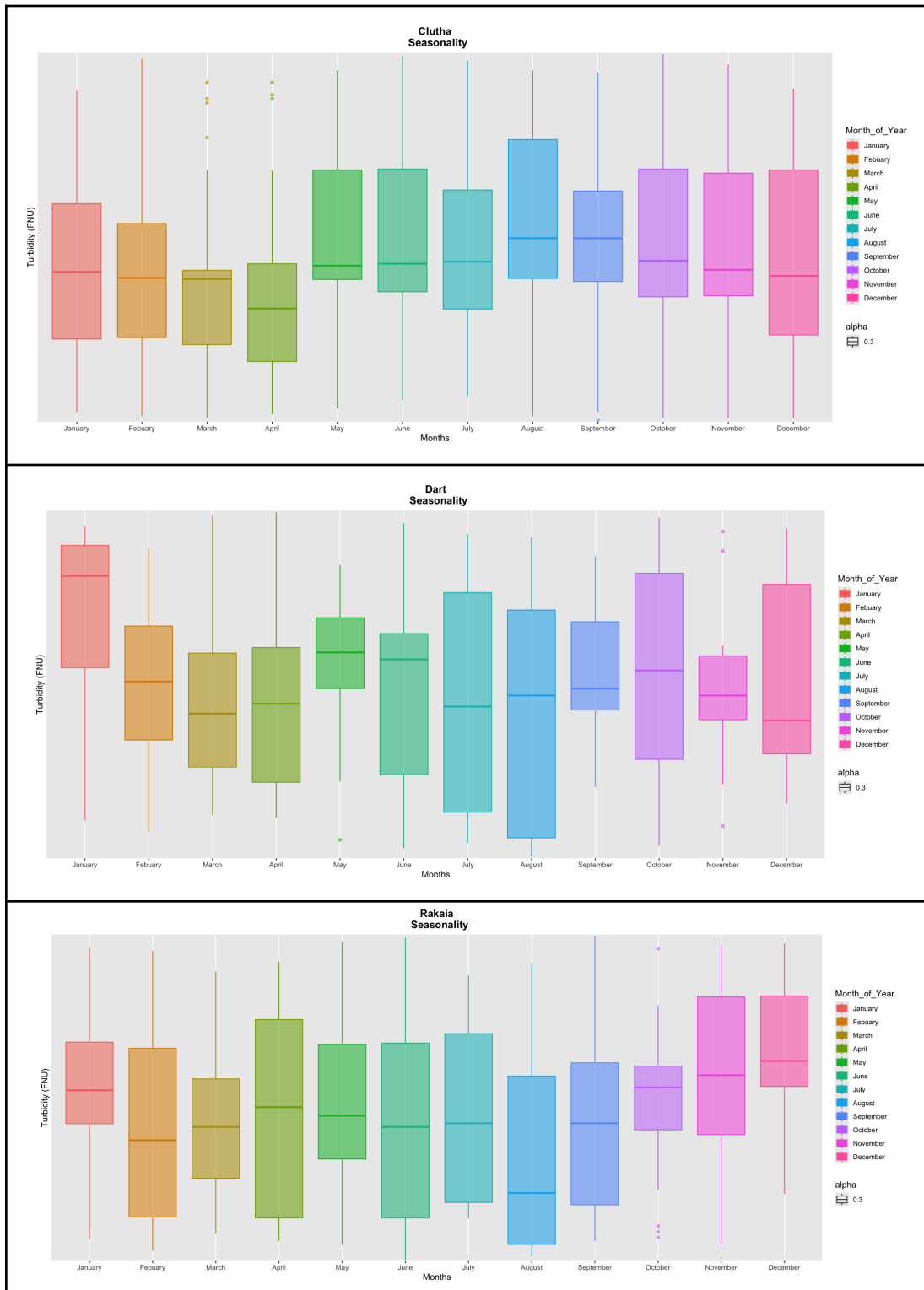
**Fig. 4** River Turbidity Comparison



**Fig. 4** This figure charts the turbidity values under 100 FNU for the three rivers. The value of 100 FNU was chosen due to Clutha River's turbidity not exceeding 90 FNU, and Dart and Rakaia Rivers seldom exceeding 100 FNU, allowing for a complete picture of Clutha River, and a near-complete picture of Dart and Rakaia Rivers, while still maintaining readable scale.

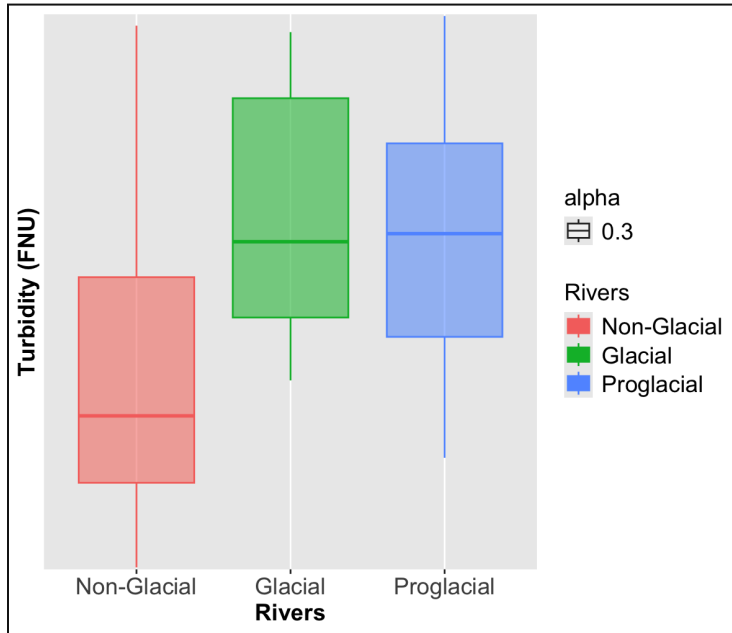
In terms of seasonal variabilities, Clutha River displays its lowest average of values in April, while its smallest range of values is in September. Its highest average of values is in August, and its largest range of values is in December. Dart River displays its lowest average of values in March, while its smallest range of values is in November. Its highest average of values is in January, and its largest range of values is in August. Rakaia River displays its lowest average of values in August, while its smallest range of values is in October. Its highest average of values is in December, and its largest range of values is in April.

**Fig. 5** Individual River Turbidity Seasonality



**Fig. 5** Seasonality of Clutha, Dart, and Rakaia rivers. Compiled using combined values of each month from every year of the study period.

**Fig. 6** Austral Summer Seasonality Comparison



Rakaia and Dart Rivers display a meltwater signal that increases turbidity during the austral summer months (December, January, February). This can be seen with constrained high mean values during this time period. December, January, and February were chosen to represent this phenomenon when comparing the three systems. Dart River experiences higher variability, yet Rakaia has a slightly higher mean value. Clutha River, being non-glacial, does not display this signal.

### 3.2 Sentinel-2 Results

**Table 4.** Satellite Stats

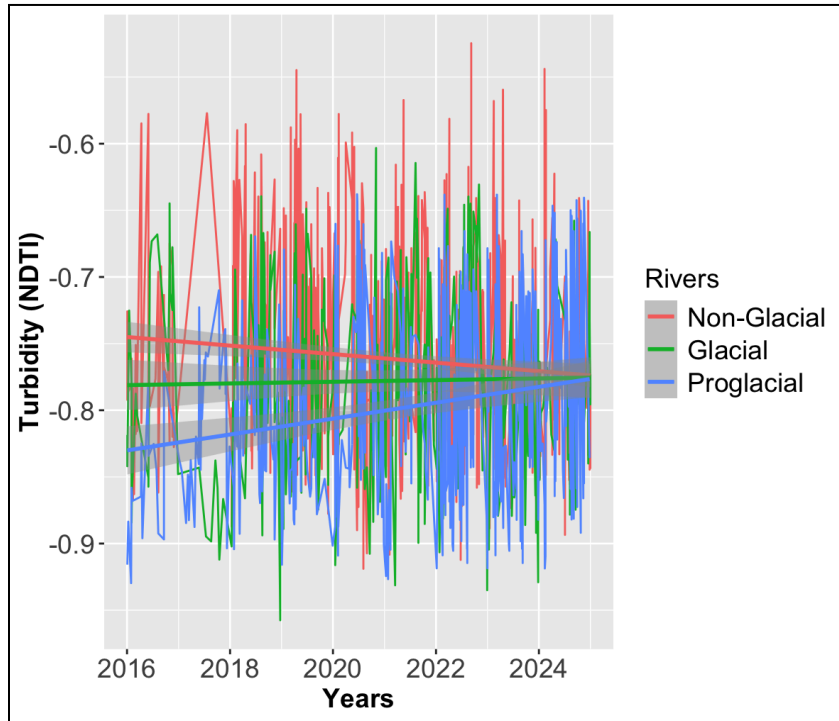
Site Name	Clutha	Dart	Rakaia
Mean Turbidity	-0.7619	-0.7779	-0.7986
Median Turbidity	-0.7711	-0.7850	-0.8114
Standard Deviation	0.0683	0.0714	0.07410411
Interquartile Range	0.0924	0.1126	0.1143
Mean Absolute Deviation	0.0672	0.0786	0.0788
Min Turbidity Value	-0.9189	-0.9575	-0.9297
Max Turbidity Value	-0.5246	-0.6032	-0.6379
Range	0.3943	0.3543	0.2917

The trends presented in the satellite data present differently from the *in situ* data, with Clutha River’s lakes (Hawea, Wanaka, and Dunstan) displaying higher average rates of turbidity than the glacial rivers’ lakes. The average values of the Clutha River system lakes have a mean turbidity of -0.7619, with a minimum value of -0.9189, a maximum value of -0.5246, and a range of 0.39423. The Dart

River system lakes average values have a mean turbidity of -0.7792, a minimum value of -0.9571, a maximum value of -0.9297, and a range of 0.2917792. The Rakaia River system lakes average values have a mean turbidity of -0.7986, a minimum value of -0.9297, a maximum value of -0.6379, and a range of -0.2917. From this, the Clutha system has the widest variability of

values, as well as the highest values. Dart has the second highest variability and maximum value, and Rakaia has the lowest.

**Fig. 7.** Lakes Turbidity Trend Comparison (Grouped by River System)



**Fig. 6** This figure charts the complete time series of the lake data, grouped by watershed. There is an observable gap of data in 2017, when four of the lakes lacked usable data. NDTI values are relative, and not indicative of NTU or FNU values as seen in traditional in situ turbidity sampling.

When examined over the study period, there are several gaps in the data due to cloud coverage interference and excess reflectance that disagreed with the model’s processing. For Hawea, Wakana, Dunstan, and Wakatipu, there was no viable data available for 2017. For Lyndon, there was a lack of data for 2016, 2017, 2018, 2019, and 2021. These gaps in data could have potential bearing on the results. Despite this concern, problematic years were removed while charting the data, and it remains apparent that the observable trends were not artifacts of the missing years, and were consistently representative of the complete study period graph.

While Clutha, as reflected in the raw statistical data, begins above the glacial systems, it trends downwards over the study period. Dart remains relatively stable with a slight upward trend, while Rakaia begins below the other systems but increases in average turbidity until all three systems converge towards relatively the same level at the end of the study period. Outlying peaks in the upper range of the data can be attributed to Clutha, while lower peaks are observable for both Rakaia and Dart. However, at the end of the study period, data becomes comparatively uniform and compact, with peaks dissipating on either end of the value range.

### 3.3 Combined Results

**Table 5.** Results Comparison

	Glacial Watershed	Glacial Watershed (Proglacial Lake)		Non-Glacial Watershed
		New	Existing	
<b>In Situ Data (Rivers, FNU)</b>	Median: 19.0	X	Median: 4.95	Median: 1.50
	Trend: Stable	X	Trend: +	Trend: +**
<b>Satellite Data (Lakes, NDTI)</b>	Median: -0.7850	X	Median: -0.8114	Median: -0.7711
	Trend: Stable***	X	Trend: +***†	Trend: -**
<b>Vowels et al. (2025) (Rivers, SSC (mg/L))</b>	Median: 346	Median: 234	Median: 159	X
	Trend: +	Trend: -	Trend: -	X

**Table 5.** This table compares the in situ and satellite data with the data from Vowels et al. (2025), the similar study that collected proglacial lake stream data in the Gulf of Alaska. Vowels et al. examined rivers with newly-formed upstream proglacial lakes, existing upstream proglacial lakes, and those without.

† Lakes Lyndon and Coleridge are glacially-fed, but not influenced by the proglacial lakes in this system, and therefore cannot be counted towards proglacial lake sedimentation trends. They are included for the secondary purpose of calibration between in situ and satellite imagery in the study, as well as further data for analysis of complex glacial systems.

#### 3.3.1 Statistics

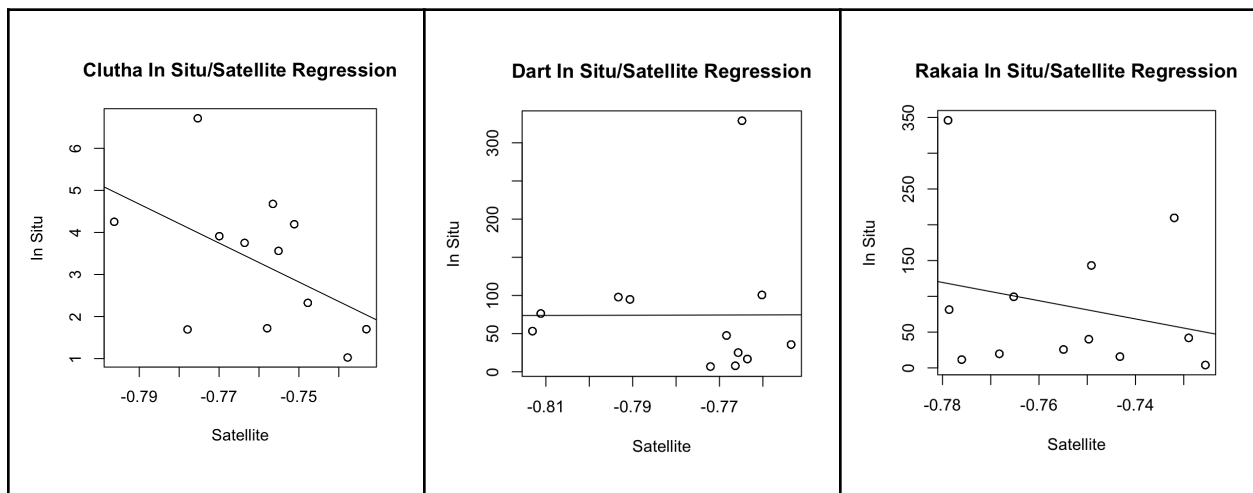
The strongest trends are identified in the lakes via the satellite imagery results. While the Clutha River system average turbidity values have the highest median and mean, they are decreasing over the study period with a strong statistical significance according to a p-value of 0.0016. Contrary to this, the Rakaia River system possesses the smallest values in the satellite data, however, its turbidity is increasing over the study period with a very strong statistical significance according to a p-value of 0.0002. The Dart River system remains relatively stable over the span of the study period. However, the statistical significance of this stability is very strong ( $p = <2e-16$ ).

The *in situ* river turbidity trends yield differing results. The Clutha River system according to the *in situ* data is increasing turbidity over the study period (2004-2023), according to a strong statistically significant p-value of 0.0010. This is in contrast to the lakes of the Clutha River system decreasing in turbidity over time. When adjusted to the constraints of the satellite study period (2016-2024), the Clutha River turbidity yields no statistically significant trend.

The *in situ* results from the Dart River system, similar to its satellite imagery counterpart, appears stagnant over the course of the study period. In this case, it does not possess a statistically significant trend, nor does it develop statistical significance when adapted to the satellite study period. It does appear visually to be in decline when plotted, suggesting the possibility of a significant trend developing in the future.

While the Rakaia River system had a very strong trend of growth displayed in the satellite results, it bears no statistically significant trend in the *in situ* data, with the river turbidity trend returning a p-value of 0.1687, hardly comparable to the lakes in the system. The trend was even less significant ( $p = 0.6648$ ) when constrained to the satellite study period.

**Figure 8.** Regression Analysis Comparison

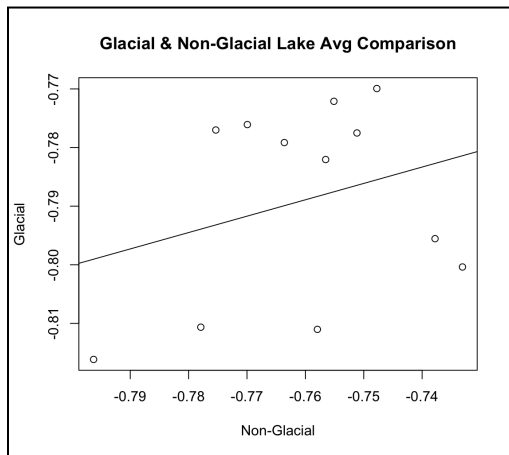


Data is retrieved from each month of the satellite and in situ data, averaged by the mean, and plotted against each other. Each point on the above plots represents the intersection between the combined monthly average of the two. When plotted against each other, the combined month averages further illuminate the statistical relationships between the *in situ* and satellite trends. Clutha River demonstrates the strongest trend ( $p = 2.04e-07$ ), which suggests a correlation between the two measurements. The correlation is negative, which confirms from the initial data analysis; that the Clutha River is increasing in turbidity whereas the associated lakes are decreasing in turbidity.

Rakaia River regression displays a negative trend with significance proportional to a p-value of 0.012. This trend is possibly corroborated by the fact that the apparent positive trend in the *in situ* data was not statistically significant, whereas the satellite data demonstrated a

strong positive trend in lake turbidity. The two are negatively statistically correlated, but in a less meaningful magnitude than the Clutha River system, indicating opposing behaviors. The Dart River regression analysis remains stable throughout, and does not possess a statistically significant trend. The Dart river data also appears to be the least cohesive of the three data sets, with an insignificant p-value of 0.9726, suggesting an incoherency between satellite and *in situ* data, or as an artifact of the lack of a significant trend in either dataset.

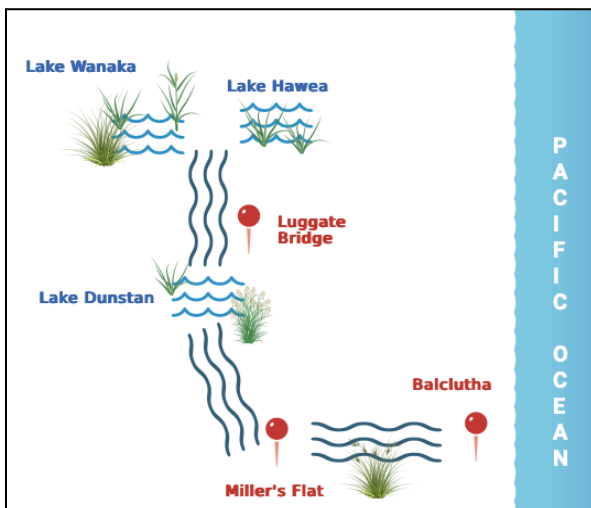
**Fig. 9** Glacial vs. Non-Glacial Regression



In order to compare the potential differences and similarities between glacial and non-glacial systems, the glacial lakes of the Rakaia River system and the Dart River system were grouped together and averaged for their monthly values. They were then regressed against the average monthly values of the lakes from the non-glacial Clutha River system. The two were not statistically related, returning a disparate p-value of 0.3507. This indicates that they behave as two separate categories. This is corroborated by the satellite data, in which the Clutha River system lakes return higher turbidity values than both Rakaia and Dart.

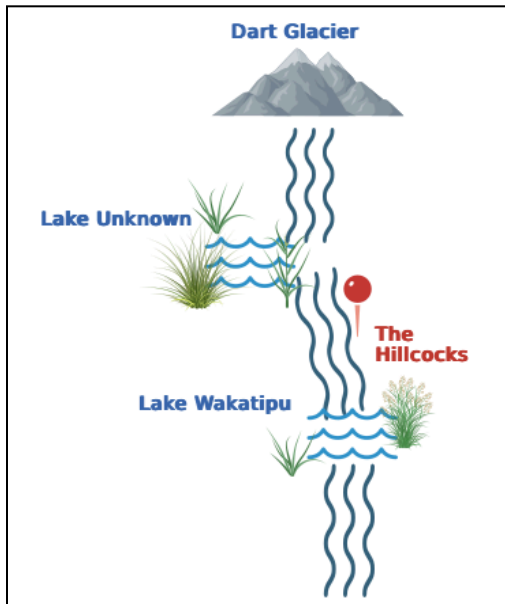
### 3.3.2 Downstream and Upstream Hydrology

**Fig. 10** Clutha River Sampling Map



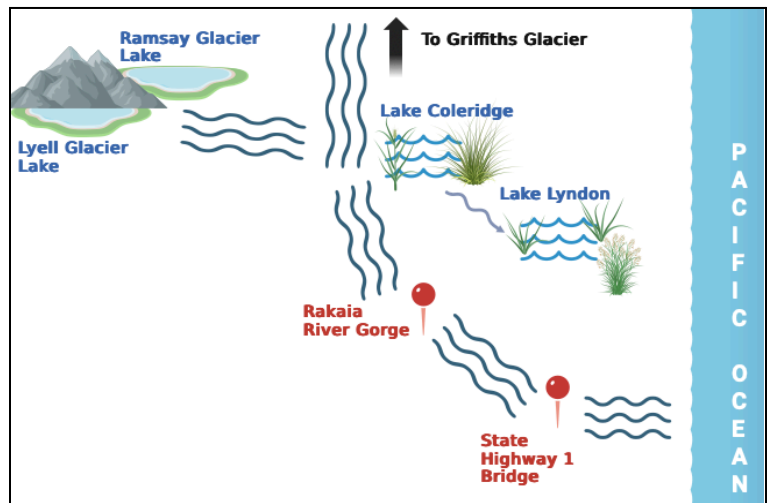
Clutha River *in situ* sampling was conducted at three locations, the first of which, Luggate Bridge, is affected by sediment levels in Lake Wanaka and Hawea, being downstream from the contributing lakes. The second and third, Miller's Flat and Balclutha, respectively, are additionally affected by Lake Dunstan, with Balclutha likely having a lower grade of impact due to its location being further removed from the rest of the system.

**Fig. 11** Dart River Sampling Map



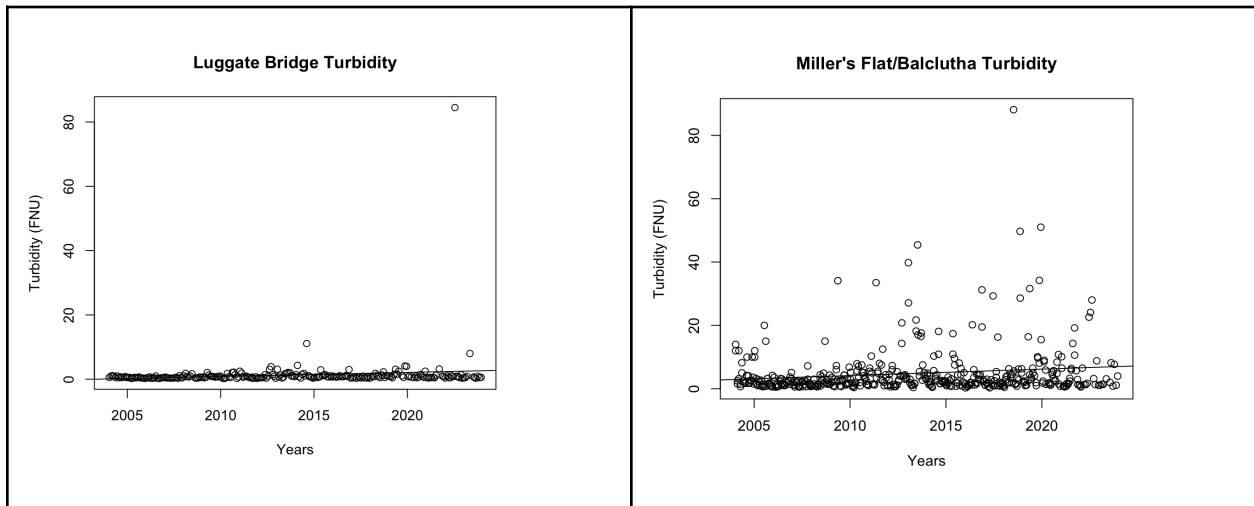
Dart River sampling was conducted downstream of Lake Unknown and the river's source at the Dart Glacier, yet upstream from Lake Wakatipu. Therefore, *in situ* sampling is subject only to sediment re-distribution by Lake Unknown. Satellite data would have a similar profile.

**Fig. 12** Rakaia River Sampling Map



Rakaia River's sampling sheds light on a complicated hydrological system. Lake Coleridge is fed by The Rakaia River's glacial source at proglacial lakes Ramsay and Lyell from the West, as well as from Griffith's Glacier via the Wilberforce River from the North. Lake Lyndon feeds back into the Rakaia River post-convergence with the Wilberforce. This invalidates the attribution of either of the lakes as being affected by proglacial lake sedimentation, but still implicates them with the *in situ* data. The first sampling site, Rakaia River Gorge, is located below both Lake Coleridge and Lyndon, which means that it is affected by their sedimentation, as well as that of the proglacial lakes at Rakaia's source. The second sampling site, State Highway Bridge 1, is similarly affected, although likely at a less intense magnitude, considering it is located further downstream.

**Fig. 13** Clutha Upstream/Downstream Comparison



In order to parse the difference in Clutha *in situ* sampling before and after passing through Lake Dunstan, and subsequently, an area of industrial development and farmland, two datasets were created; Luggate Bridge (upstream of Lake Dunstan), and Miller's Flat/Balclutha (downstream of Lake Dunstan). Luggate Bridge is fed by Lakes Hawea and Wanaka, and yields lower and less varied turbidity values, with a mean of 1.345 FNU. It displays a slight upward trend with moderate statistical significance according to a p-value of 0.0416. Meanwhile, Miller's Flat and Balclutha turbidity values are much more varied, with a stronger positive trend ( $p = 0.0025$ ).

**Fig. 14** Clutha Upstream/Downstream Regression



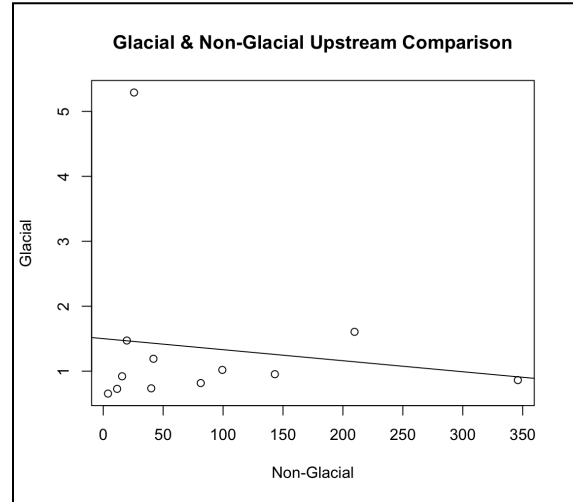
The upstream and downstream Clutha River sampling sites are moderately positively correlated ( $p = 0.0365$ ), with outliers at both sites resulting in a less coherent correlation. These outliers can be identified on the site's individual plots. For Luggate, it experienced its maximum value of 84.5 on July 7th, 2022, while Miller's Flat/Balclutha recorded its highest value of 88.1 on July 11th, 2018. Clutha River experiences its highest monthly averages in June, July, and August, with August being the highest and most varied. Due to both values being in July during Clutha River's most turbid season, these outliers can likely be attributed

to seasonal streamflow. Disregarding these outlier disruptions, the two plots are largely in

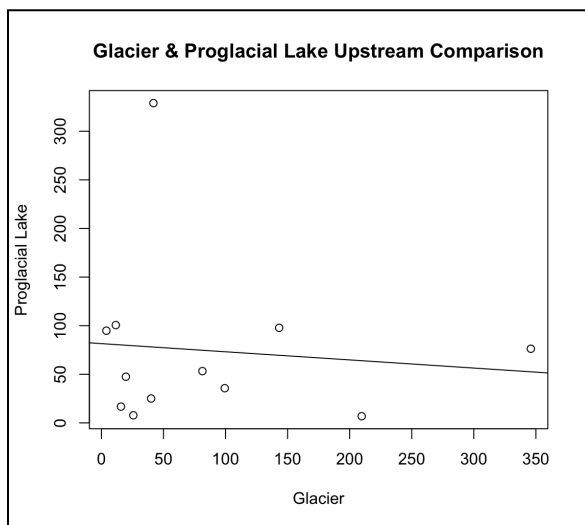
alignment, although Miller’s Flat and Balclutha return a wider variety of values than Luggate Bridge, as demonstrated by the former’s range of 87.82 versus the latter’s of 84.26.

**Fig. 15** Glacial vs. Non-Glacial Upstream Regression

Luggate Bridge is downstream of two non-glacial lakes. Rakaia River Gorge and Highway State Bridge Crossing are downstream of two glacial lakes. They are effectively quite similar sites, sans the glacial source variable, and are thus compatible for comparison. Regression analysis of their monthly averages reveals that they lack any statistically significant relationship ( $p = 0.6713$ ). The slight negative trend on the regression plot additionally suggests that there is an opposing trend between the two categories. Rakaia River’s maximum value is 97, which is higher than Luggate Bridge’s maximum of 84.5. Rakaia River also possesses a broader range of values; 96.6 compared to Luggate Bridge’s 84.26. Luggate Bridge returns a mean turbidity value of 1.345, which is several magnitudes lower than Rakaia River’s mean turbidity of 62.879.



**Fig. 16** Glacial vs. Proglacial Lake Upstream Regression



When comparing the sampling sites for Rakaia River and Dart River, there is no statistical correlation or identifiable trend between the two ( $p = 0.7611$ ). They are slightly negatively correlated, also suggesting differing behaviors. An outlier is present, which also appeared in Fig. 15, indicative of Dart River’s spike in turbidity.

## 4. Discussion

### 4.1 *Interpretation*

This study observed that glacially-derived riverine sites were more turbid than non-glacial sites, with glacial sites that lack an upstream proglacial lake being the most turbid, and evidently different in behavior than glacial sites that possess an upstream proglacial lake. Vowels et. al. (2025), determined that sites with upstream proglacial lakes were found to have lower and declining SSC. While the *in situ* data from Rakaia River (the system with upstream proglacial lakes), was less turbid than Dart River, which lacked such features, it did not have a statistically significant declining trend. The discrepancy between our results could be explained either by this study's small sample size, geographic differences, or outside hydrological variables such as irrigation run-off, terrigenous sediment deposits, and miscellaneous anthropogenic effects. Despite this difference in trend, the *in situ* findings between glacial sites were consistent with Vowels et. al (2025). Vowels et. al (2025) did not survey non-glacial sites nor lakes within the systems sampled, and therefore a comparison cannot be made in those regards.

Results differed for satellite observations of lakes, which identified the non-glacial system, Clutha River, as being the most turbid, although in significant decline. The glacial system without an upstream proglacial lake, Dart River, was the second-most turbid, and was largely stagnant, lacking a significant trend like its river sampling counterpart. The glacial system with an upstream proglacial lake, Rakaia River, was the least turbid, but demonstrated a strong significant positive trend. Regression analysis revealed that the riverine and lacustrine systems are negatively correlated. This can either be attributed to a genuine natural discrepancy between the two as components of a hydrological system due to differences in sediment transport in dynamic fluvial environments versus sediment trapping in lakebeds, or as an unreliability of the satellite imaging techniques. As suspended sediment transported through fluvial systems settle in lakes, it is possible that satellite imagery may not reflect true sedimentation, as values are calculated according to relative surface water reflectance.

Rakaia River is remote for the majority of its run, never encountering large development, and a relatively small margin of farmland. It is sourced by several glaciers in the Southern Alps without discernible anthropogenic influence. This eliminates sedimentation to primarily, or in some cases, exclusively, geological and glacial sources. Dart River is similarly sourced by a remote glacier with limited anthropogenic influence along its run into Lake Wakatipu, making the two sites comparable. Clutha River is sourced relatively remotely from Lakes Hawea and Wanaka, allowing sampling taken at Luggate Bridge prior to disruption by development and farmland run-off to be comparable to sampling in Dart and Rakaia. Luggate Bridge is less turbid than Miller's Flat and Balclutha, sampling sites downstream of Lake Dunstan. This is an indicator of land use as a source of turbidity in Clutha River. Regression analysis between Luggate Bridge and sampling in Rakaia (both sites with influence from two upstream lakes, with

Rakaia influenced by glacial and proglacial lake processes), revealed no identifiable correlation, indicating that glacial processes are variables of disruption for a watershed. (Fig. 15)

Proglacial lakes act as sediment traps, disrupting downstream sedimentation. (Carrivick and Tweed, 2013) This effect can be seen in the comparison between Dart River, a glacial system lacking an upstream proglacial lake, and Rakaia River, which has two. Dart River has a significantly higher mean turbidity of 115 compared to Rakaia, which has a mean value of 62.8, Dart River additionally has higher maximum values of turbidity, and wider value range than Rakaia, indicating less contained variability. (Table 3) Additionally, despite both sampling sites being below the streamflow of two lakes and a glacier, they are not correlated, indicating the presence of proglacial lakes upstream of the Rakaia River sampling sites is likely responsible for decreased sediment compared to Dart River. (Fig. 14) Despite these differences, the two glacial systems are removed from the turbidity values sampled in the Clutha River by an order of magnitudes. (Fig. 4) Clutha River experienced higher rates of sedimentation downstream, yet remained far behind the values of the glacial rivers.

While proglacial lakes may effectively trap sediments in glacial systems as compared to glacial systems without an upstream proglacial lake, the comparison does not appear consistent for systems in which glacial deposits are not present. This suggests that proglacial lakes, while acting as lacustrine sediment sinks for glacial debris, are not effective enough to simulate lower sediment rates seen in non-glacial systems. Therefore, the 'effectiveness' of a proglacial lake sediment trap can be measured as strong as compared to other glacial systems, but not strong enough to mitigate the effects of glacial sedimentation in comparison to non-glacial conditions.

Through sediment coring efforts in Norway, it was suggested that proglacial lakes experience higher rates of sedimentation when glaciers are calving, and that glacial streamflow and grain size of sediment fluctuations can also impact the increment of sediment that is delivered into a proglacial lake. (Bogen et. al, 2013) It was noted that despite these variables, downstream sedimentation remained relatively low, however, this is not necessarily the case for Rakaia River, which experiences a constrained range of highest values during the austral summer months, starting in January, possibly correlating to summer glacial melt. (Fig. 5) These constrained values indicate consistency across years, which solidifies the trend. Dart River also displays the meltwater signal, beginning in December, earlier than Rakaia. (Fig. 6) Due to both systems displaying similar meltwater patterns, it would appear that increased glacial melt likely does have an effect on downstream sedimentation. Clutha River, being non-glacial, does not display the signal, lending to a different seasonality pattern, which aids in distinguishing the glacial system seasonality as unique, and attributable to increased glacial meltwater.

Lacustrine sedimentation as indicated by satellite modelling returns the lowest turbidity values for Rakaia River. While the lakes fed by/into the Rakaia River are increasing in turbidity with time, they lack inflow from the proglacial source, and are instead sourced by glaciers that feed the Wilberforce and Harper Rivers. They are hydrologically implicated with Rakaia River's *in situ* data, however, they cannot be categorized as influenced by an upstream proglacial lake. Therefore, their increasing trend does not negate the results of Vowels et. al. (2025). The lakes of

Dart River are verifiably stable in their turbidity, which are greater in value than that of Rakaia, but less than Clutha. Clutha's Lakes are highest in turbidity, but declining with time. The statistical negative correlation between Clutha's lakes and rivers is, as previously addressed, either a matter of sediment transport differences or satellite inaccuracy.

#### 4.2 Recommendations

This study was limited in scope, and therefore invites and encourages further exploration of proglacial lake effects as glacial retreat progresses globally. Investigating additional drivers of turbidity such as local terrigenous sedimentation and glacial calving/melting rates is encouraged. This study used a limited NDTI value range (-1:-0.5). It is suggested that in order to test the effectiveness of NDTI, that value range should be expanded in further studies. Additionally, *in situ* sampling should be taken in the lakes where satellite imaging was employed in order to further assess the usability of remote sensing techniques for turbidity. The reverse can also be applied, such that the rivers can be imaged and analyzed remotely if possible.

Further study is welcomed in other geographic areas to continue the global verification of proglacial lake behavior, as well as an expansion of sites throughout the Southern Alps. Different variables can be introduced, such as varying amounts of lakes, contributing tributaries and glaciers, and surrounding land use. Most importantly, lakes that are hydrologically influenced by an upstream proglacial lake should be incorporated for comparison to non-glacial and glacially-influenced lakes, such as those that were used in this study.

#### 5. Conclusion

Glaciers in New Zealand have only been substantially retreating since 2008. (Mackintosh et al. 2017) Study surrounding the impacts of proglacial lake development on downstream environments is emerging as glaciers disappear, and has great bearing on our need to understand landscapes resulting from global climate change, a need that deepens every year. While proglacial lakes do act as sediment traps, downstream sedimentation still fluctuates in accordance with glacial melt. It is unclear how sustainable new proglacial lakes are as they continue to grow. In comparison to non-glacial systems, even those with more industrial development and irrigation, rivers with upstream proglacial lakes are still substantially turbid, which can have negative effects downstream. (Carey et al. 2017)

This study recommends that stream and river clean-up efforts be directed towards glacial systems, and that those with upstream proglacial lakes be carefully monitored for seasonal and decadal turbidity trends in order to evaluate the continued effectiveness of proglacial lakes as sediment traps for glacial debris. Eventual storage loss for sediment hosted in lakebeds is inevitable, and could prove detrimental downstream, but evaluating when or how that may be is essential. This is not to say that proglacial lakes should be monitored on geological time, but

instead that their sediment transport rates, turbidity, and downstream effects should be recorded in order to develop an accountable database on proglacial lake behavior.

Per this study's observations, it is suggested that the role of proglacial lakes as sediment traps in riverine systems is verifiable, but not effective enough to offset the sedimentation effects of glacial debris as opposed to non-glacial systems. This is evidenced by the discrepancy between the turbidity levels in Dart and Rakaia Rivers compared to Clutha River, as well as Clutha River's lack of a seasonal glacial meltwater signal corresponding to a rise in turbidity. Additionally, this study observes that satellite NDTI values may be unreliable forms of measurement, as they rely on surface water reflectance, and cannot account for the whole water column. The negative correlation between the satellite and *in situ* data does not discourage or invalidate the analysis of downstream lacustrine glacial sedimentation. Instead, this is a phenomenon that must be more closely studied in order to further understand the broader implications of glacial debris and proglacial lake formation on downstream lakes, as well as the relationship of sediment transport between lakes and rivers.

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