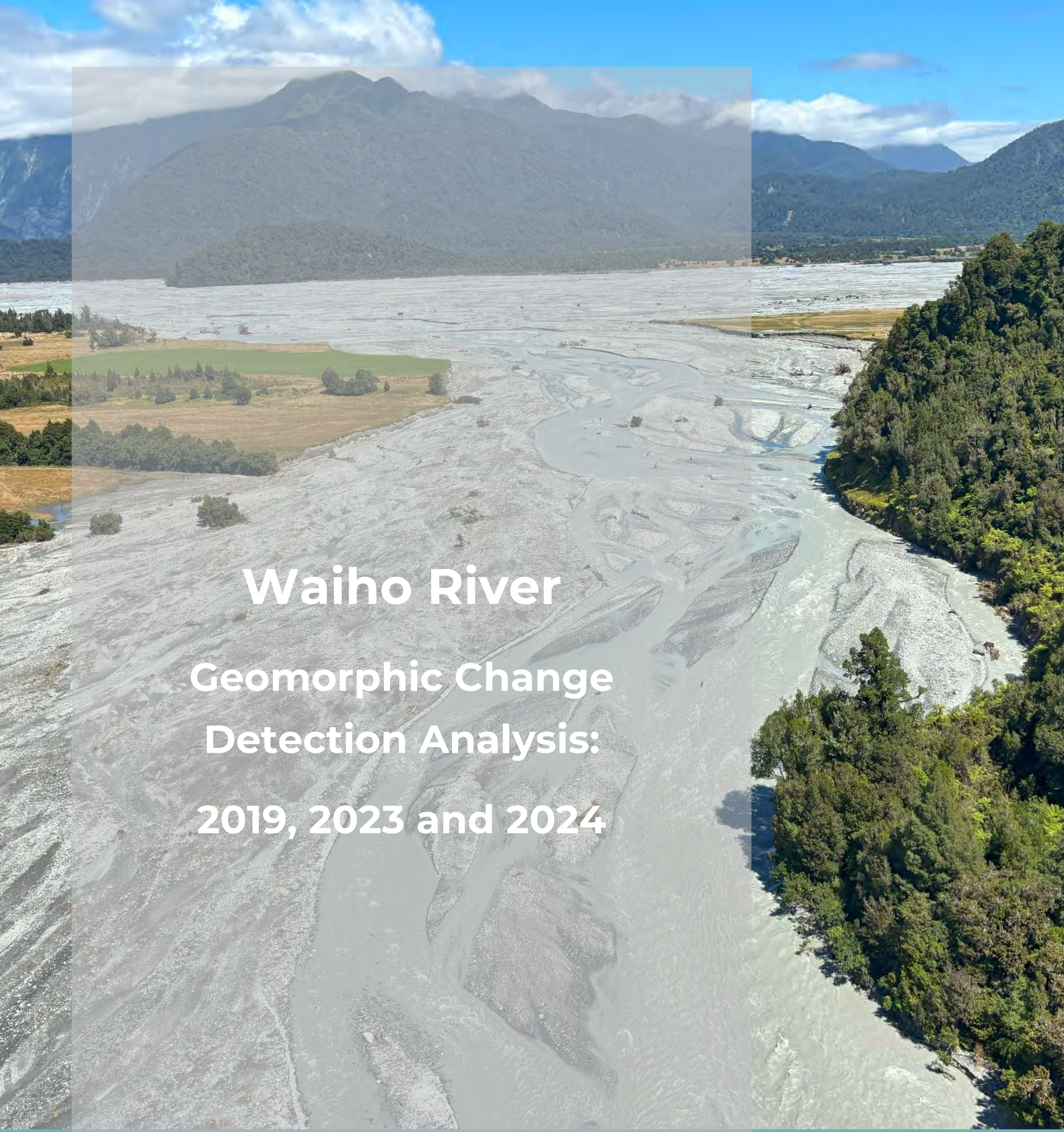

Waiho River

Geomorphic Change Detection Analysis: 2019, 2023 and 2024

25 March 2024

Client: West Coast Regional Council

Report by: Rose Beagley & Matthew Gardner
Land River Sea Consulting Limited
www.landriversea.com

Land River Sea CONSULTING

THE WEST COAST REGIONAL COUNCIL

REVISION HISTORY

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Date:	25 March 2024	
Revision:	02	
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TABLE OF CONTENTS

1. INTRODUCTION

1.1. SCOPE

Land River Sea Consulting has been contracted by the West Coast Regional Council (WCRC) to carry out an analysis of the change in bed levels which have occurred in the Waiho River between 2016, 2019, 2023, and 2024. In particular, this study focuses on the changes which have occurred since 2023 as well as the developing avulsion of the Waiho River into the Tatare Stream upstream of the Waiho Loop.

1.2. CONTEXT

The Waiho River is located on the West Coast of the South Island of New Zealand and drains from the Western slopes of the Southern Alps and across a 16 km long floodplain, to the Tasman Sea (Figure 1-1).

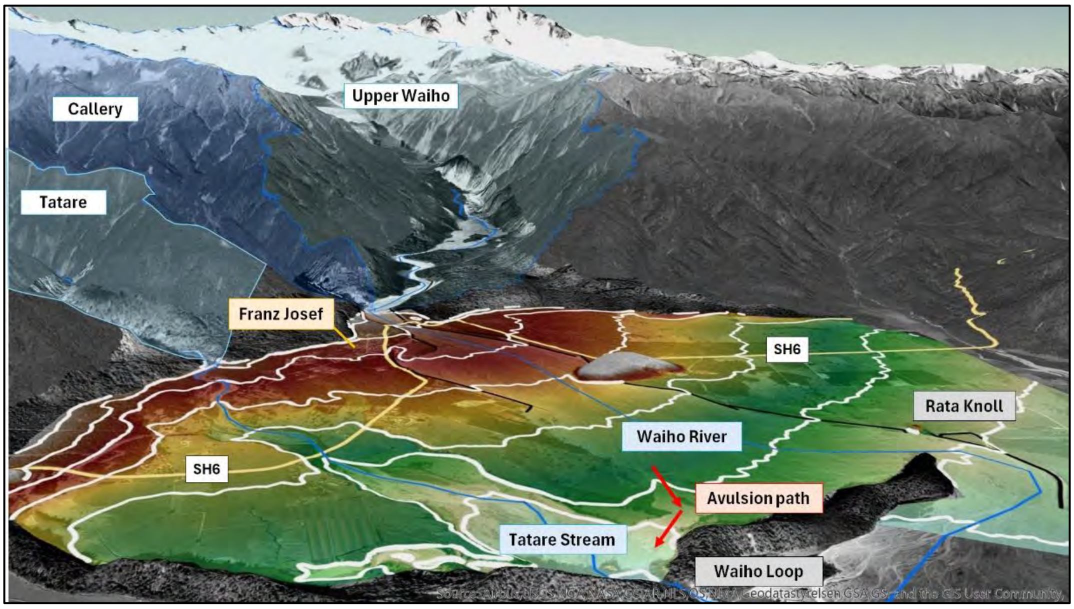
Figure 1-1 – Location map of the Waiho River highlighting the two main subcatchments that feed the river (Callery and upper Waiho).

The upper part of the catchment is comprised of two main subcatchments – the Callery and the upper Waiho (Figure 1-1 and Figure 1-2). The Callery has multiple small glaciers in its upper reaches that feed into a steep, long and narrow gorge. The upper Waiho hosts the rapidly receding Franz Josef glacier.

Immediately downstream of the junction between the Callery and the Waiho rivers, the Waiho River is crossed by the State Highway 6 (SH6) Bridge which is operated by Waka Kotahi - New Zealand Transport Authority (NZTA) and flows adjacent to the town of Franz Josef / Waiau, situated on the true right bank of the river. This marks the start of the 16 km long floodplain.

In the upper reach of this floodplain, from the SH6 Bridge down to the Waiho Loop (a terminal moraine feature) the river widens out into a natural alluvial fan (Figure 1-2). However, the current fan is constrained by man-made stopbanks, which have forced the river to aggrade in its current alignment, rather than naturally deposit sediment over a wider area. This has resulted in the need for ongoing upgrades to the stopbank network to contain the river. Additionally, this aggradation has built up the Waiho fan surface so that it is now level with the Tatare fan surface.

- The Tatare flows to the north (true right side) of the Waiho, and previously has joined the Waiho just downstream of the Waiho Loop.
- Since the early 2000's floodwaters from the Waiho have on occasion overtopped the Tatare fan surface, with small and brief breakouts reaching the Tatare upstream of the Waiho Loop. Yet the river was always able to be rediverted away from the Tatare Stream and fan surface.
- However, because the Waiho fan is now level with the Tatare fan, in February 2023 a significant flow path (avulsion channel) developed from the Waiho into the Tatare upstream of the Waiho Loop. This channel continued to deepen and widen over the following 12 months, and in January 2024, 95% of the Waiho flow was using this channel. Since then, this percentage of flow has fluctuated as the channel network shifts across the fan surface, alternating the amount of flow going through the gap between Rata Knoll and the Waiho Loop, and down the avulsion into the Tatare Stream.



Land River Sea
CONSULTING

Figure 1-2 – June 2023 LiDAR contours and shaded DEM of the Waiho and Tatare fans. Labels denote the Franz Josef township, Waiho Loop, Rata Knoll, avulsion path, SH6, and Callery, Tatare and upper Waiho subcatchments labelled.

2. DATA COLLECTION

2.1. LIDAR

A summary of the LiDAR data used for the analyses in this report is provided in Table 2-1. The data was supplied in the form of a 1 m DEM together with a raw point cloud in LAS (.las) format classified into ground and non-ground points.

The elevation accuracy of the resulting 3D point cloud was assessed using checkpoint survey observations acquired on bare earth surfaces. The average difference and standard deviation of differences between the checkpoints and locally interpolated point cloud are included in Table 2-1. LiDAR datasets for all survey years had low standard deviation (SD) and root mean square (RMS) error suggesting minimal bias.

Table 2-1 - Summary of LiDAR data

	2016	2019	2023	2024
Collection Date	June 2016	16 April	8 June	31 January
Collected By	New Zealand Aerial Surveys Ltd	Waikato University	University of Canterbury	
Collection Method	Fixed wing aircraft	Helicopter	Helicopter	
Sensor	Optech Orion H300	Riegl VUX-1LR	Riegl VUX240	
Altitude	1190-2375 m	350 m	300 m	
No. checkpoint surveys	(Unknown)	97	298	1640
Standard deviation of checkpoint/point-cloud difference	0.016 m	0.017 m	0.051 m	0.047 m
Average checkpoint/point-cloud difference	0.007 m	0.001 m	-0.006 m	0.003 m
RMS error	(Unknown)	0.017 m	0.051 m	0.047 m

2.2. CROSS-SECTIONAL SURVEYS

Cross-sectional survey data from the Franz Josef Glacier terminus to the Waiho Loop has been collected since 1983, with the most recent complete survey carried out by Chris J Coll & Associates in April 2016. Cross-section locations are provided in Figure 2-1. For further information on this survey data see previous reports (Gardner, 2016; Gardner & Brasington, 2019).

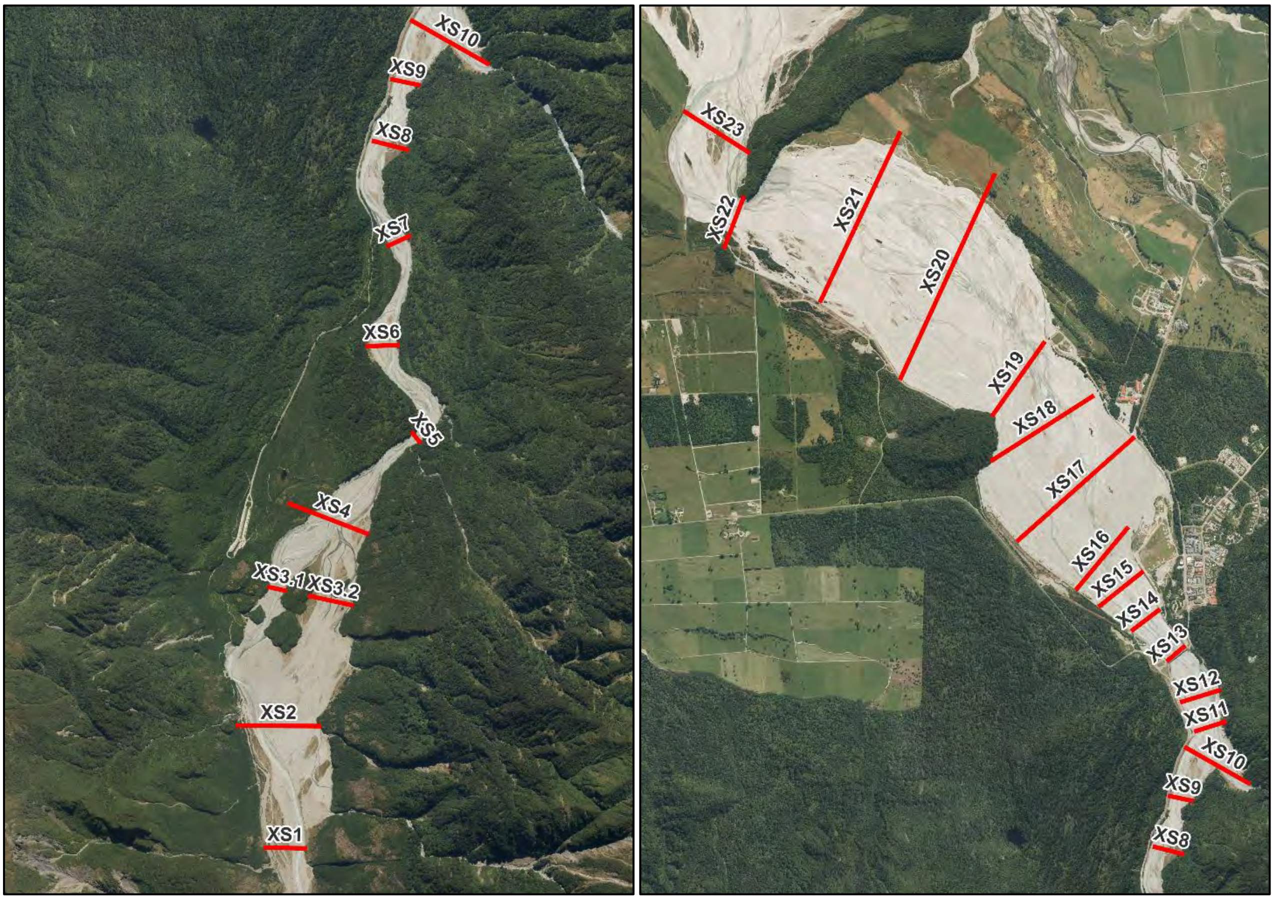


Figure 2-1 – Cross-section locations.

The mean bed level (MBL) for each cross-section has been calculated by extracting and averaging the elevation values from the 2019, 2023 and 2024 LiDAR surveys along each cross-section line. Plots of the change in mean bed level at each cross-section (relative to 1983 MBLs) were published in the Gardner and Brasington (2019) report and have been extended to include the data from 2023 and 2024 – see Appendix A.

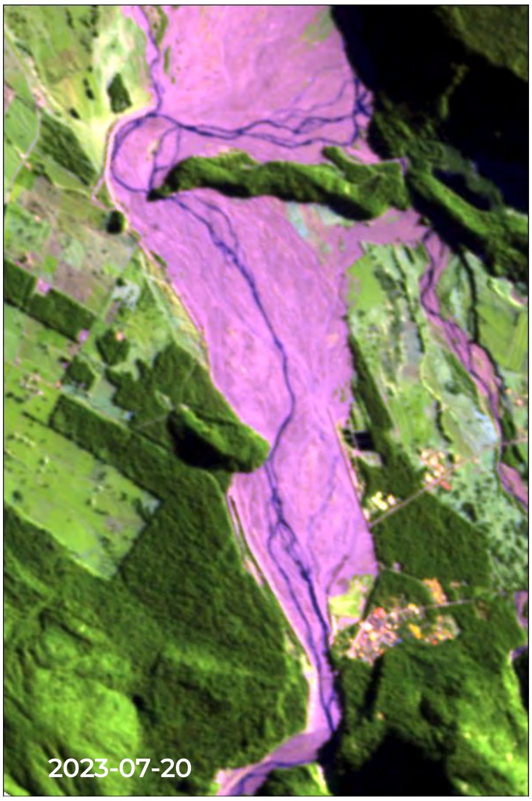
This cross-sectional data and MBL analysis have been used in both the geomorphic change detection (GCD) results and the discussion sections to provide a longer record of bed level change.

2.3. SATELLITE IMAGERY

To assist with understanding the influence the Waiho fan surface has on channel patterns, as well as how this has and may continue to affect the development of the avulsion, we have downloaded satellite imagery from the Sentinel Hub. Fourteen cloud-free images from the Sentinel-2 L2A (atmospherically corrected) data source have been downloaded in False Colour (Urban) at a 10 m resolution (Table 2-2). An example has been included below.

The full set of downloaded Sentinel imagery is presented in Appendix B.

Table 2-2 – Dates and an example of downloaded cloud-free Sentinel Hub satellite imagery.



Date
2023-02-10
2023-02-25
2023-03-22
2023-04-06
2023-05-11
2023-06-05
2023-07-20
2023-07-25
2023-08-09
2023-09-03
2023-10-18
2023-11-17
2023-12-07
2024-01-26

We have traced the main channel of the Waiho River in each of these satellite images and then overlaid them with one and five metre contours from the 2023 and 2024 LiDAR DEMs in order to see how much influence the shape of the fan has on where the main channel flows and therefore its likelihood to flow down the avulsion channel, further developing it.

This analysis has been used in the discussion of the Waiho fan aggradation and shape in section 5.1.

2.4. HYDROLOGY

Rainfall data has been provided by the West Coast Regional Council at two monitoring sites within the Waiho catchment (Figure 2-2 and Table 2-3).

Table 2-3 – Rainfall and water level monitoring sites in the Waiho catchment.

Monitoring site	Owner	Elevation	Data	Period
Waiho Rv at SH6	WCRC	146 m	Rainfall/Water level	2009 to current
Waiho Rv at Douglas Hut	NIWA	221 m	Rainfall	1983 to current

Figure 2-2 - Locations of the monitoring sites used in this analysis.

2.4.1. RAINFALL DATA

From the rainfall data timeseries recorded by each site we have extracted:

- Daily rainfall totals for the February 2023 and January 2024 weather events
- Monthly totals for all years and long-term monthly means

We have also completed frequency distribution analyses (Gumbel; calendar year) within the Hilltop software for a range of durations including:

- **Short:** 1, 2, and 3 hours
- **Medium:** 6, and 12 hours
- **Long:** 1, 2, 3, and 6 days

Given the Waiho Rv at Douglas Hut site has a much longer timeseries, we ran the frequency distributions for its entire timeseries (1983 to 2024) and for the same period of data available for the

Waiho Rv at SH6 site (2009 to 2024). This allowed us to see how the annual recurrence intervals (ARIs) changed with more data and between the two sites:

- **Short:** ARIs remained the same.
- **Medium:** ARIs increased from the 2009-2024 analyses to the 1983-2024 analyses by 0.1 year
- **Long:** ARIs increased from the 2009-2024 analyses to the 1983-2024 analyses by between 0.1 to 0.3 years.

ARIs between the two sites were also very similar, with differences between 0.1 and 0.3 years.

As the ARIs between the two sites aren't significantly different we have chosen to use the frequency distribution analysis for the full time series at the Waiho Rv at Douglas Hut site. This has allowed us to include the bigger events that occurred during the previous positive phase of the Interdecadal Pacific Oscillation (IPO; discussed in section 6.2) and therefore provided better context to the events that triggered and rapidly developed the avulsion, and for what may be expected now that we have entered another positive phase of the IPO.

3. GEOMORPHIC CHANGE DETECTION - METHODOLOGY

3.1. GCD SOFTWARE

The GCD analysis has been undertaken using the Geomorphic Change Detection toolkit (GCD, see gcd.riverscapes.xyz) developed by James Brasington (University of Canterbury), Joe Wheaton (Utah State University) and Philip Bailey (North Arrow Research).

The GCD toolkit facilitates the measurement of bed level change by comparing time-series of digital elevation models and accounting for the uncertainty that arises from survey instrument errors, interpolation artefacts, surface roughness and the pattern of spatial sampling. Users are therefore able to classify the probability that elevation differences observed between two DEMs are likely to be significant (real) relative to the underlying data uncertainty.

See the previous Waiho GCD report "Waiho River: Change Detection Analysis" (Gardner & Brasington, 2019) for further information.

3.2. DEM UNCERTAINTY MODELLING

A spatial model of DEM uncertainty was constructed for each surface (2016, 2019, 2023 and 2024) based on the observed pattern of land cover.

Given the high quality (low magnitude of vertical errors reported) of the four LiDAR datasets, the surface cover has first order control on data quality. This reflects the combined effects from vegetation cover on the ability to of the LiDAR survey to penetrate through to ground level, the local surface roughness (e.g., riverbed gravels vs pasture) and laser reflectivity – in particular the lack of data retrievals on wet/inundated areas. To represent these effects, surface error masks (Figure 3-1 and Figure 3-2) were developed for all four datasets.

- For the 2016 and 2019 data, automatic image classification tools were used on the imagery from the Sentinel 2 platform using a supervised classification of the land cover at a 10 m resolution.
- For the 2023 and 2024 data, areas of significant change from the 2016 and 2019 datasets were manually delineated from high resolution orthoimagery for each survey.

For each land cover class, an estimated vertical uncertainty was set, guided by the local pattern of elevation uncertainty revealed in the raw point cloud. The resulting land-cover classification and DEM elevation uncertainty is shown in Table 3-1.

Note that there was significantly more water present during the 2024 survey as it was flown immediately following a weather event due to the urgency of the situation (i.e. 95% of the Waiho flowing down the avulsion channel). This has increased the uncertainty in the DEM.

Table 3-1 – Vertical uncertainty values four the GCD analyses.

Land Cover Class	Characteristic Vertical Uncertainty (m)
Grass	0.15
Exposed river gravels	0.13
Tall vegetation	0.30
Inundated areas (without correction)	0.50
Inundated areas (with section corrections, 2016 only)	0.25
Coastal water (2024)	0.75
Deep water (through the Tatare cut in 2024)	1.00

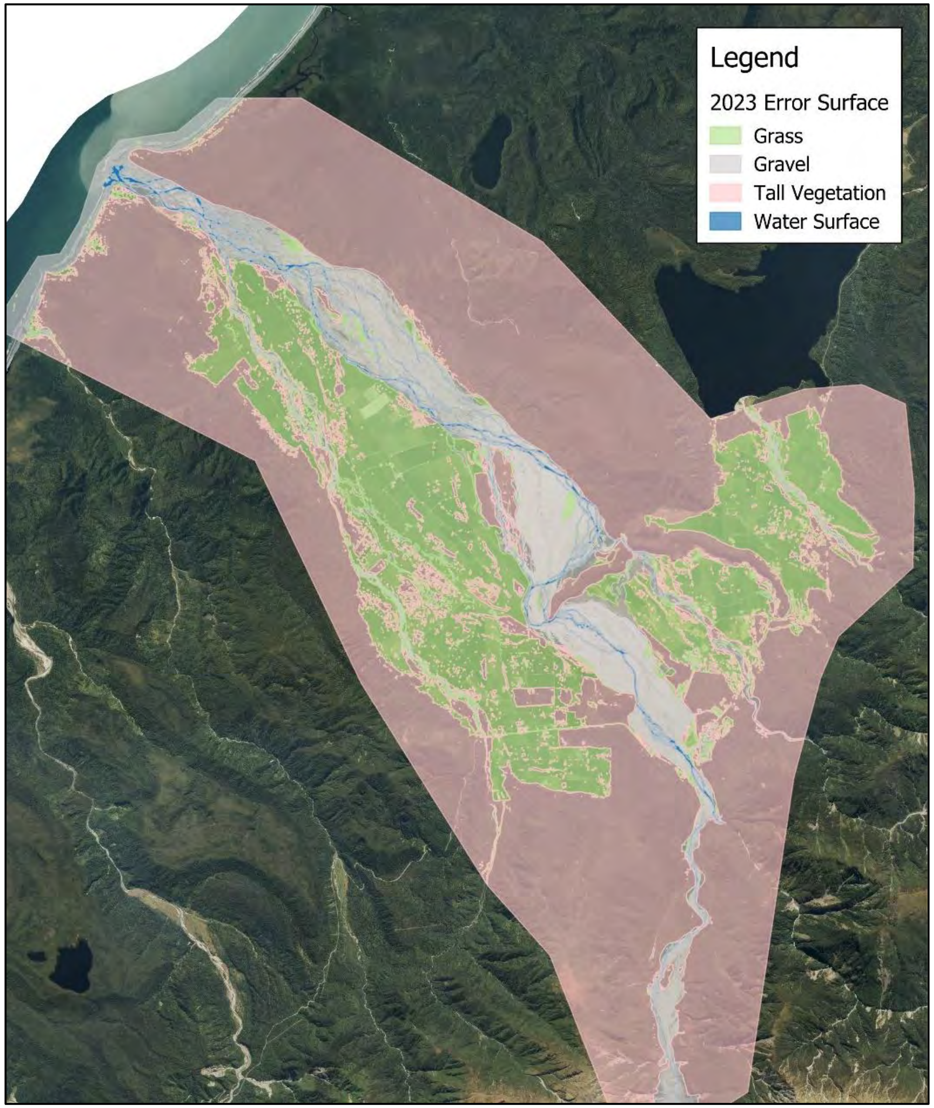


Figure 3-1 – Uncertainty mask 2023 LiDAR

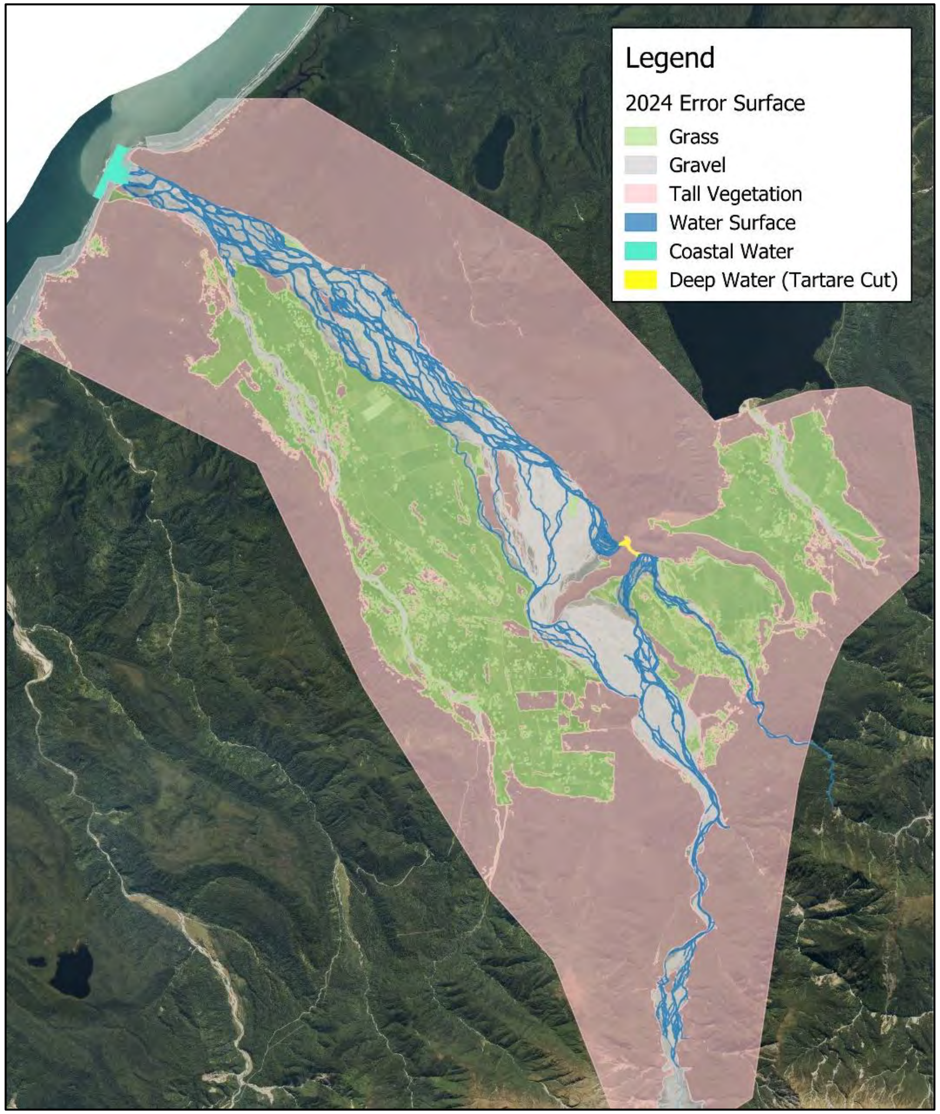


Figure 3-2 – Uncertainty mask 2024 LiDAR

3.3. BROADSCALE AREAS OF INTEREST

There are two broadscale areas of interest (AOI) for the geomorphic change detection (GCD) analysis. These have been defined as the active channel of the Waiho River (from glacier to sea), and the Tatare Stream (from the range front to where it joins the Waiho downstream of the Waiho Loop).

These areas of interest are presented in Figure 3-3 below.

Figure 3-3 - GCD areas of interest (AOI)

To better understand how the Waiho-Tartare avulsion is developing, there is an additional area of interest which extends from the start of the incision at the top of the avulsion to the toe of the fan forming downstream of the Tatare cut through the Waiho Loop. The avulsion area of interest is shown in Figure 3-4.

Our GCD analysis of this area compares the volume of erosion through the avulsion channel, and widening of the cut in the Waiho Loop, with the volume of deposition occurring in the Tatare as a result of the avulsion.

Figure 3-4 – Avulsion extent AOI over the 2024 ortho image.

3.4. SUB-REACH CHANGE DETECTION UNITS

A more detailed analysis of the Waiho River has been carried out by dividing the channel into a series of downstream units or ‘budget cells’, in order to quantify the longitudinal pattern of bed-level response from the glacier to the coast.

Two different models of downstream cells were used. First, the analysis has been divided up into reaches bounded at each end by the location of historic cross section surveys (XS0-XS23). This approach provides a measure of average bed-level changes across each reach and mitigates potential bias from specific cross-section measurement locations. This cross sectional analysis has been used as it provides a consistent manner of bed level comparison with historic investigations which have been based on these historic cross section locations.

However, since the historic cross sections do not extend significantly downstream of the Waiho Loop (XS23), a separate longitudinal analysis has also been completed, in which the entire length of the river was divided into a set of regular 500 m cells based on the channel centreline. This method is advantageous in that it provides an analysis over a uniform interval for the entire river reach.

The resulting pattern of cells for the cross-sectional and 500 m delineated longitudinal models is shown in Figure 3-5 and Figure 3-6, respectively, on the following pages.

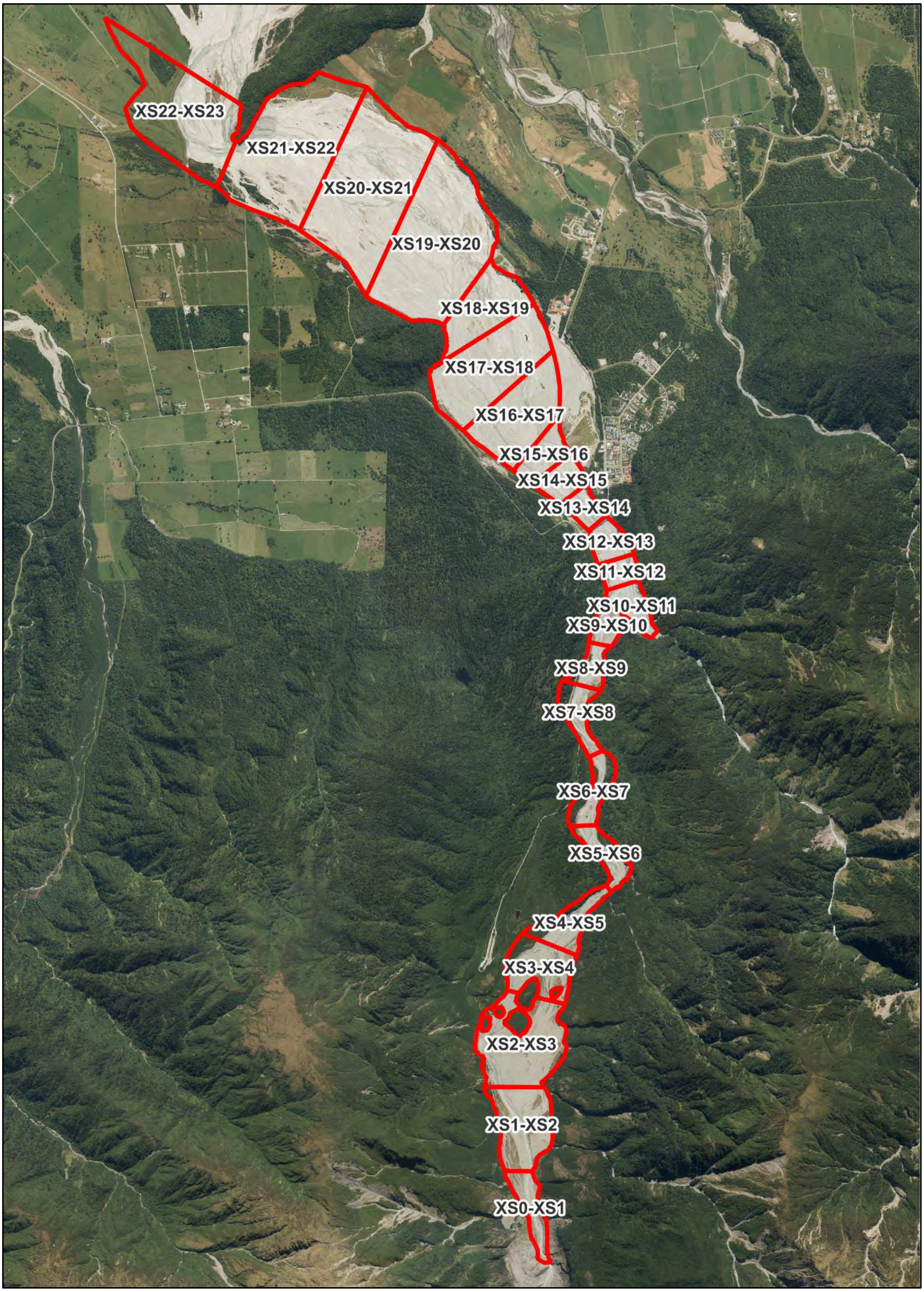


Figure 3-5 – GCD budget cells defined by the historic cross sections.

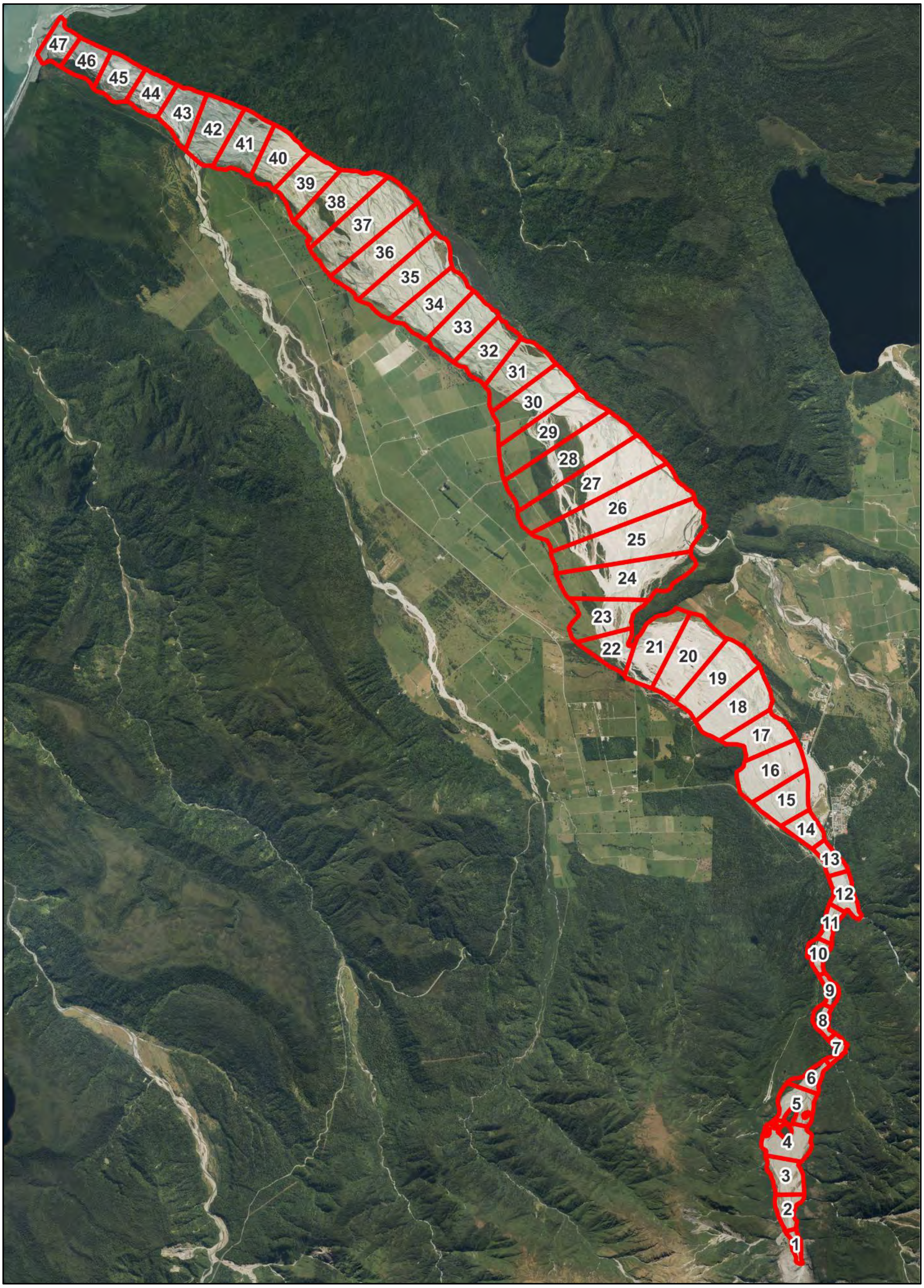


Figure 3-6 - GCD budget cells defined by 500 m cross sections.

4. GEOMORPHIC CHANGE DETECTION – RESULTS

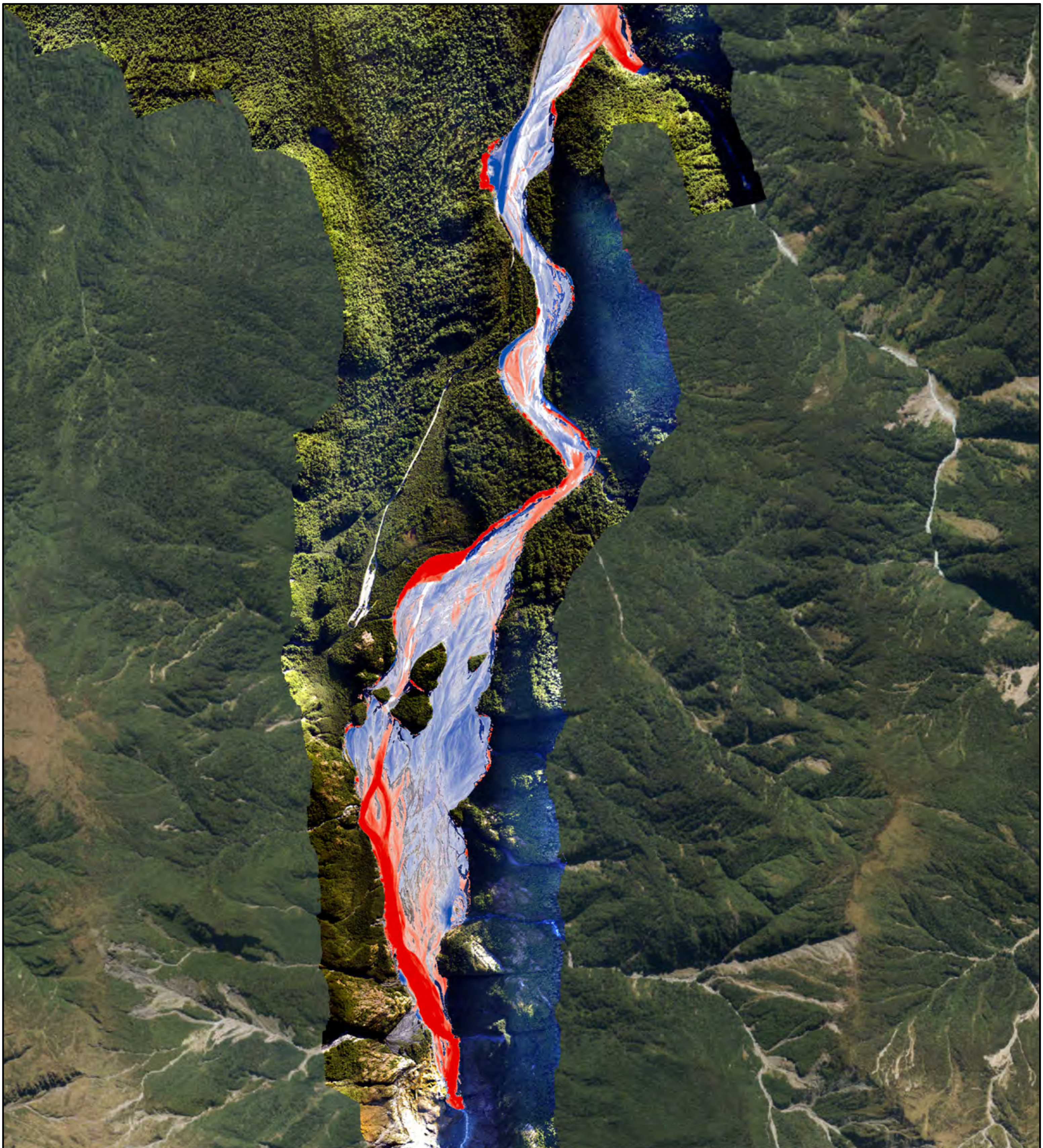
The results of three GCD analyses for the periods 2019-2023, 2023-2024 and 2016-2024 are discussed in the following sections. The findings are intended to be reviewed alongside the 2016 to 2019 GCD analysis report (Gardner & Brasington, 2019).

Areas of aggradation and degradation are visualised by DEMs of Difference (DoDs) and are provided in the maps on the following pages.

Section 4.1 presents the GCD results of the longitudinal pattern and average change in bed-level response, based on the cross-sectional and 500 m 'budget cells' extending from the glacier to the coast, as discussed in Section 3.4.

In Section 4.2, general patterns of bed level change are discussed to provide insight into the scale and speed at which sediment is transported through the Waiho and Tartare systems respectively.

In Section 4.3 more detailed analysis of bed level change is provided at a reach-based scale with the inclusion of the avulsion area.



SCALE BAR

0 0.25 0.5 1 km

PROJECT

Waiho River
Change Detection Analysis

TITLE Bed Level Change Detection
Glacier to Callery Confluence
Change in Bed Level 2019 to 2023
(95% Threshold)

Land River Sea
CONSULTING

AUTHOR	DATE	JOB CODE	REVISION
Rose Beagley	23 Feb 2024	WCRC039d	01

N

Legend
2019-2023
Elevation Difference (m)

- < -3.40
- -3.40 to -3.00
- -3.00 to -2.60
- -2.70 to -2.30
- -2.30 to -1.90
- -1.90 to -1.50
- -1.50 to -1.10
- -1.10 to -0.70
- -0.80 to -0.40
- -0.40 to 0.00
- 0.00 to 0.40
- 0.40 to 0.80
- 0.80 to 1.20
- 1.10 to 1.50
- 1.50 to 1.90
- 1.90 to 2.30
- 2.30 to 2.70
- 2.70 to 3.10
- 3.00 to 3.40
- > 3.40

SCALE BAR

0 0.25 0.5 1 km

Legend

2019-2023

Elevation Difference (m)

- < -3.40
- -3.40 to -3.00
- -3.00 to -2.60
- -2.70 to -2.30
- -2.30 to -1.90
- -1.90 to -1.50
- -1.50 to -1.10
- -1.10 to -0.70
- -0.80 to -0.40
- -0.40 to 0.00
- 0.00 to 0.40
- 0.40 to 0.80
- 0.80 to 1.20
- 1.10 to 1.50
- 1.50 to 1.90
- 1.90 to 2.30
- 2.30 to 2.70
- 2.70 to 3.10
- 3.00 to 3.40
- > 3.40

PROJECT

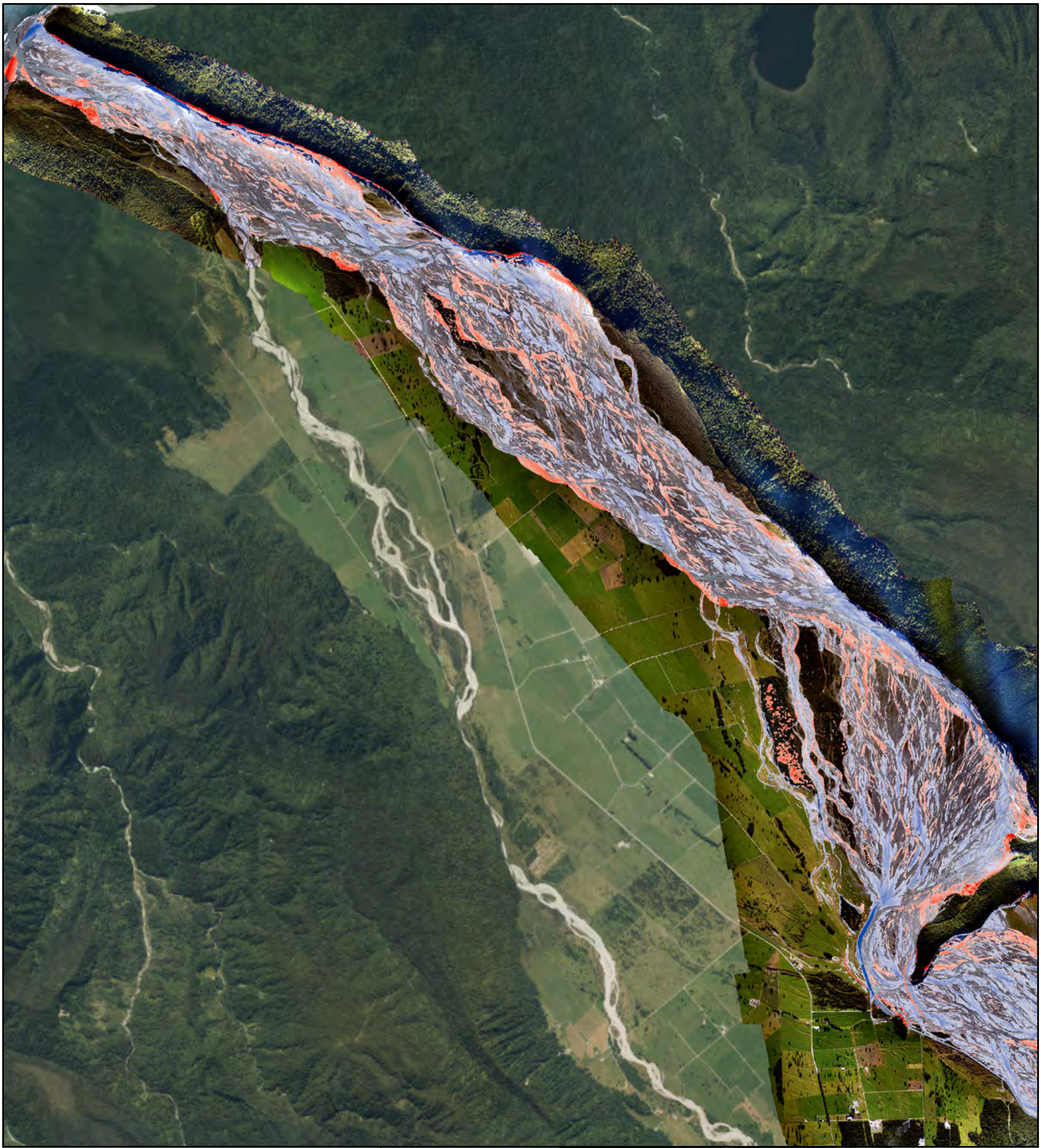
Waiho River Change Detection Analysis

TITLE

Bed Level Change Detection Callery to Waiho Loop Change in Bed Level 2019 to 2023 (95% Threshold)

Land River Sea CONSULTING

AUTHOR	DATE	JOB CODE	REVISION	N
Rose Beagley	23 Feb 2024	WCRC039d	01	



SCALE BAR

0 0.5 1 2 km

PROJECT

Waiho River
Change Detection Analysis

Legend

2019-2023

Elevation Difference (m)

- < -3.40
- -3.40 to -3.00
- -3.00 to -2.60
- -2.70 to -2.30
- -2.30 to -1.90
- -1.90 to -1.50
- -1.50 to -1.10
- -1.10 to -0.70
- -0.80 to -0.40
- -0.40 to 0.00
- 0.00 to 0.40
- 0.40 to 0.80
- 0.80 to 1.20
- 1.10 to 1.50
- 1.50 to 1.90
- 1.90 to 2.30
- 2.30 to 2.70
- 2.70 to 3.10
- 3.00 to 3.40
- > 3.40

TITLE **Bed Level Change Detection**
Waiho Loop to Mouth
Change in Bed Level 2019 to 2023
(95% Threshold)

Land River Sea
CONSULTING

AUTHOR	DATE	JOB CODE	REVISION	
Rose Beagley	23 Feb 2024	WCRC039d	01	N

SCALE BAR

0 0.25 0.5 1 km

PROJECT

Waiho River
Change Detection Analysis

TITLE

Bed Level Change Detection
Glacier to Callery Confluence
Change in Bed Level 2023-2024
(84% Threshold)

Land River Sea
CONSULTING

AUTHOR	DATE	JOB CODE	REVISION
Rose Beagley	23 Feb 2024	WCRC039d	01

N

Legend
2023-2024
Elevation Difference (m)

- < -3.40
- -3.40 to -3.00
- -3.00 to -2.60
- -2.70 to -2.30
- -2.30 to -1.90
- -1.90 to -1.50
- -1.50 to -1.10
- -1.10 to -0.70
- -0.80 to -0.40
- -0.40 to 0.00
- 0.00 to 0.40
- 0.40 to 0.80
- 0.80 to 1.20
- 1.10 to 1.50
- 1.50 to 1.90
- 1.90 to 2.30
- 2.30 to 2.70
- 2.70 to 3.10
- 3.00 to 3.40
- > 3.40

SCALE BAR

0 0.25 0.5 1 km

Legend

2023-2024

Elevation Difference (m)

- < -3.40
- -3.40 to -3.00
- -3.00 to -2.60
- -2.70 to -2.30
- -2.30 to -1.90
- -1.90 to -1.50
- -1.50 to -1.10
- -1.10 to -0.70
- -0.80 to -0.40
- -0.40 to 0.00
- 0.00 to 0.40
- 0.40 to 0.80
- 0.80 to 1.20
- 1.10 to 1.50
- 1.50 to 1.90
- 1.90 to 2.30
- 2.30 to 2.70
- 2.70 to 3.10
- 3.00 to 3.40
- > 3.40

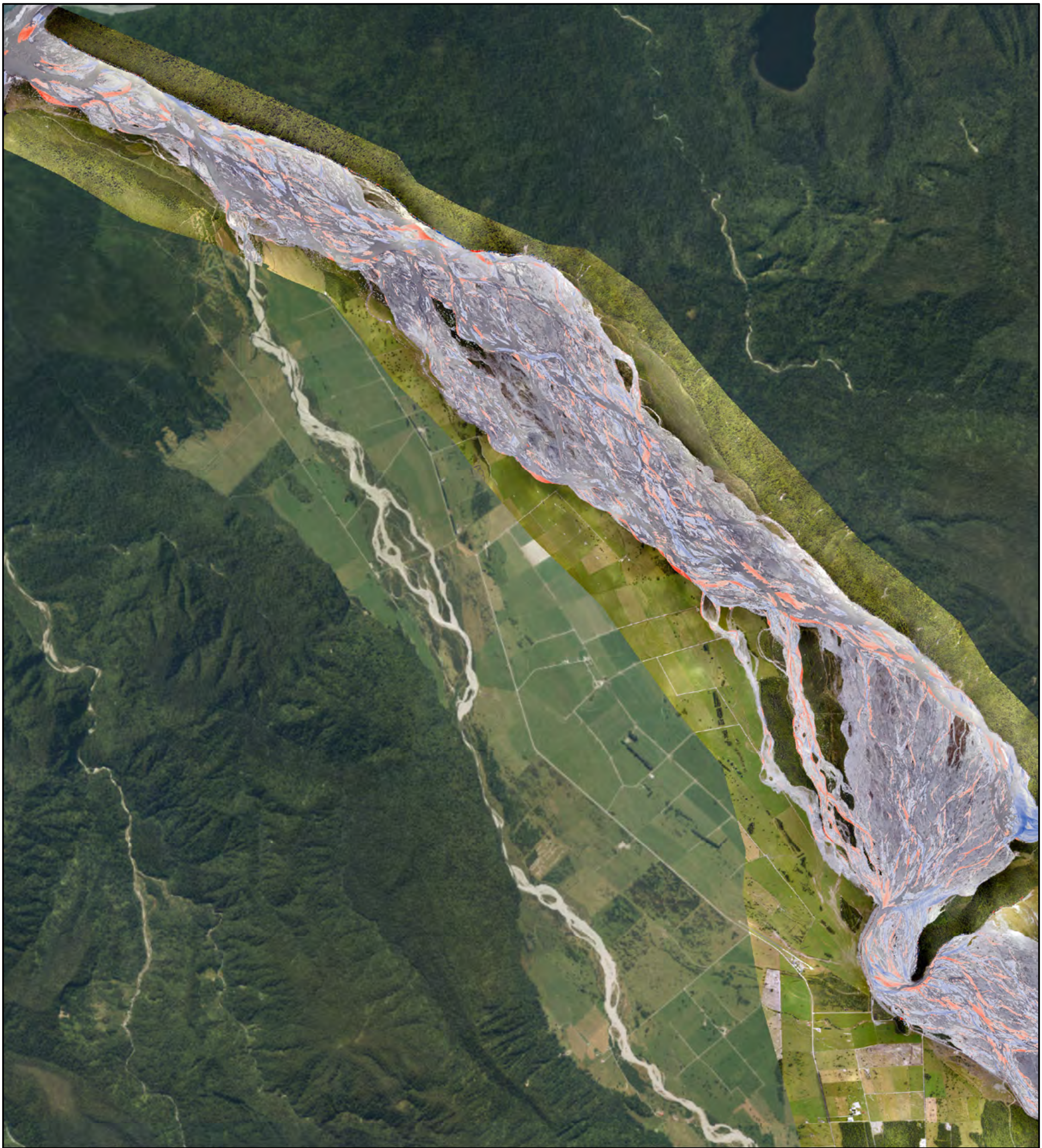
PROJECT

Waiho River
Change Detection Analysis

TITLE **Bed Level Change Detection**
Callery to Waiho Loop
Change in Bed Level 2023-2024
(84% Threshold)

Land River Sea CONSULTING

AUTHOR	DATE	JOB CODE	REVISION	
Rose Beagley	23 Feb 2024	WCRC039d	01	N



SCALE BAR

0 0.5 1 2 km

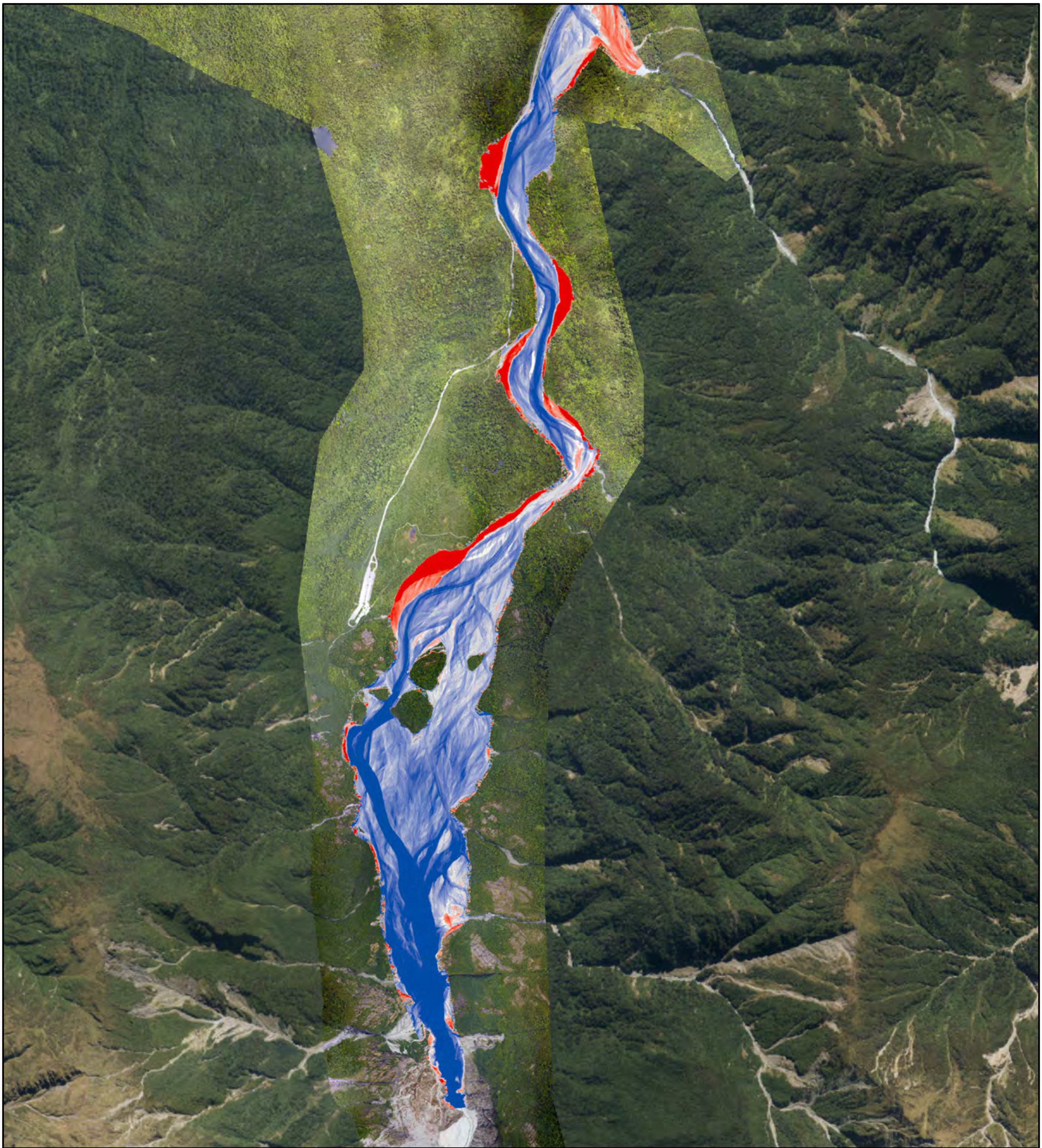
PROJECT
Waiho River
Change Detection Analysis

Legend
2023-2024
Elevation Difference (m)
- < -3.40
- -3.40 to -3.00
- -3.00 to -2.60
- -2.70 to -2.30
- -2.30 to -1.90
- -1.90 to -1.50
- -1.50 to -1.10
- -1.10 to -0.70
- -0.80 to -0.40
- -0.40 to 0.00
- 0.00 to 0.40
- 0.40 to 0.80
- 0.80 to 1.20
- 1.10 to 1.50
- 1.50 to 1.90
- 1.90 to 2.30
- 2.30 to 2.70
- 2.70 to 3.10
- 3.00 to 3.40
- > 3.40

TITLE **Bed Level Change Detection**
Waiho Loop to Mouth
Change in Bed Level 2023-2024
(84% Threshold)

Land River Sea
CONSULTING

AUTHOR	DATE	JOB CODE	REVISION	
Rose Beagley	23 Feb 2024	WCRC039d	01	N



SCALE BAR

0 0.25 0.5 1 km

PROJECT

Waiho River Change Detection Analysis

TITLE Bed Level Change Detection Glacier to Callery Confluence Change in Bed Level 2016-2024 (84% Threshold)

Land River Sea CONSULTING

AUTHOR	DATE	JOB CODE	REVISION
Rose Beagley	23 Feb 2024	WCRC039d	01

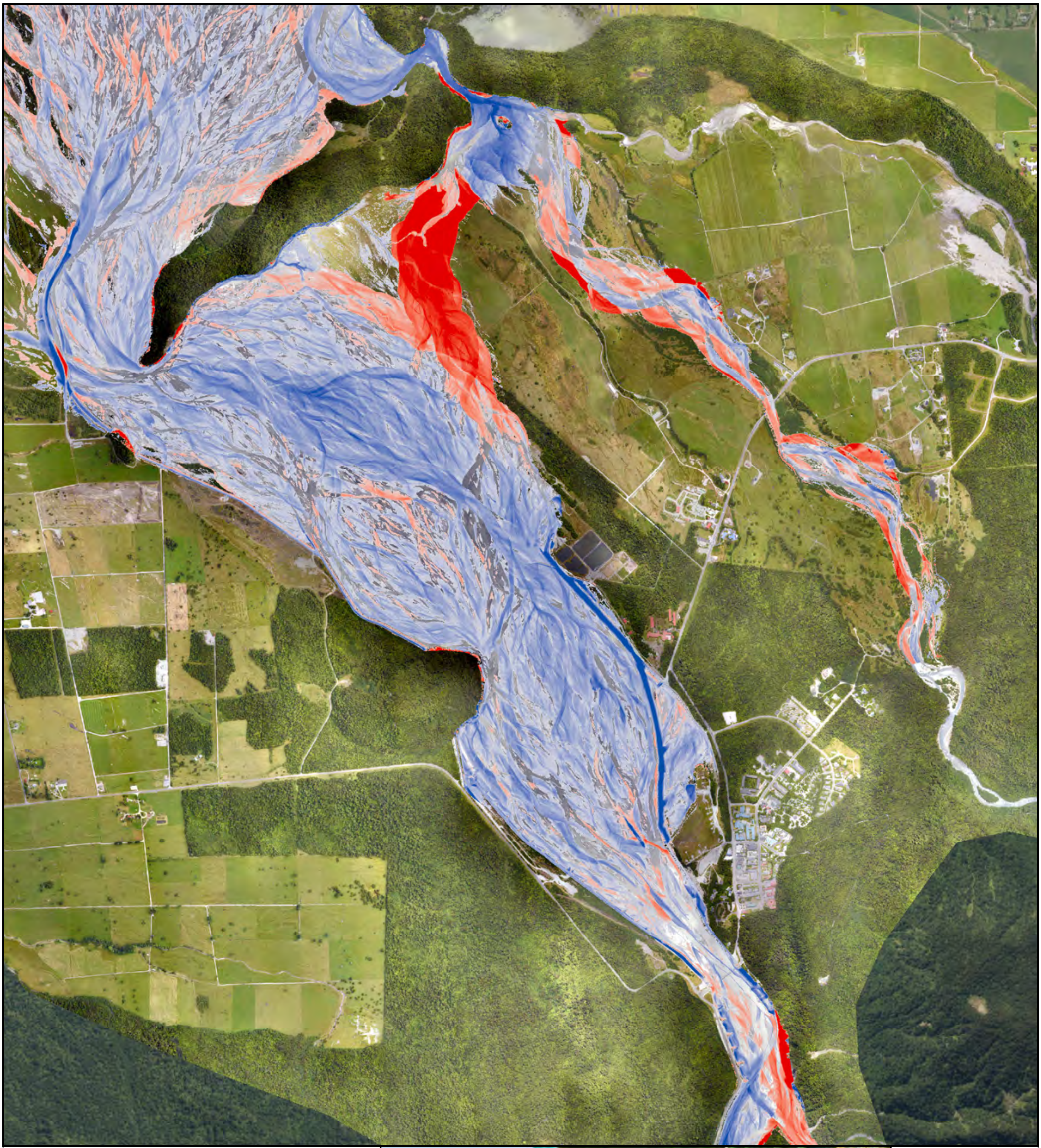
N

Legend

2016-2024

Elevation Difference (m)

- < -3.40
- -3.40 to -3.00
- -3.00 to -2.60
- -2.70 to -2.30
- -2.30 to -1.90
- -1.90 to -1.50
- -1.50 to -1.10
- -1.10 to -0.70
- -0.80 to -0.40
- -0.40 to 0.00
- 0.00 to 0.40
- 0.40 to 0.80
- 0.80 to 1.20
- 1.10 to 1.50
- 1.50 to 1.90
- 1.90 to 2.30
- 2.30 to 2.70
- 2.70 to 3.10
- 3.00 to 3.40
- > 3.40



SCALE BAR

0 0.25 0.5 1 km

Legend

2016-2024

Elevation Difference (m)

- < -3.40
- -3.40 to -3.00
- -3.00 to -2.60
- -2.70 to -2.30
- -2.30 to -1.90
- -1.90 to -1.50
- -1.50 to -1.10
- -1.10 to -0.70
- -0.80 to -0.40
- -0.40 to 0.00
- 0.00 to 0.40
- 0.40 to 0.80
- 0.80 to 1.20
- 1.10 to 1.50
- 1.50 to 1.90
- 1.90 to 2.30
- 2.30 to 2.70
- 2.70 to 3.10
- 3.00 to 3.40
- > 3.40

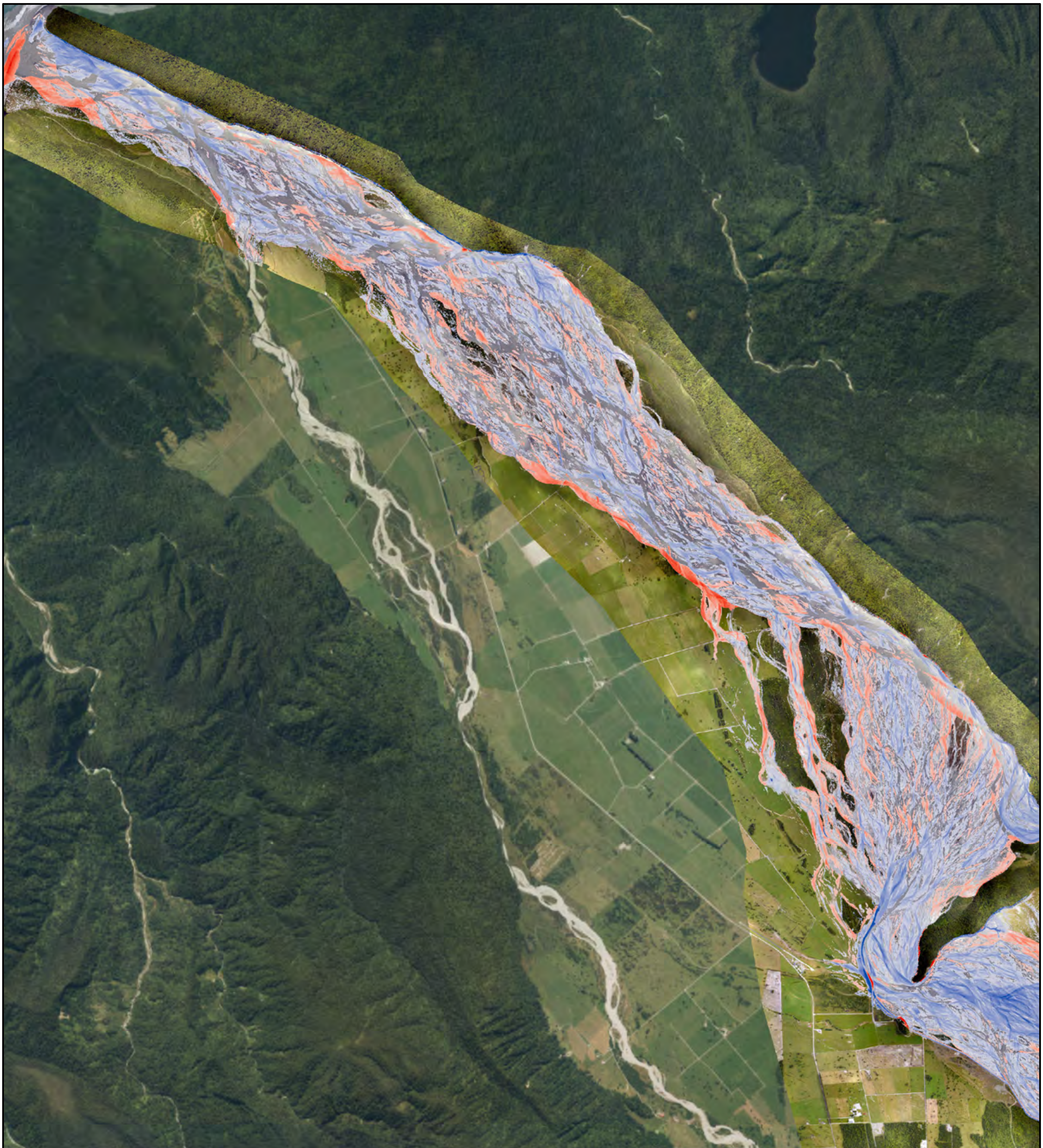
PROJECT

Waiho River
Change Detection Analysis

TITLE **Bed Level Change Detection**
Callery to Waiho Loop
Change in Bed Level 2016-2024
(84% Threshold)

Land River Sea
CONSULTING

AUTHOR	DATE	JOB CODE	REVISION	
Rose Beagley	23 Feb 2024	WCRC039d	01	N



SCALE BAR

0 0.5 1 2 km

PROJECT

Waiho River
Change Detection Analysis

Legend

2016-2024

Elevation Difference (m)

- < -3.40
- -3.40 to -3.00
- -3.00 to -2.60
- -2.70 to -2.30
- -2.30 to -1.90
- -1.90 to -1.50
- -1.50 to -1.10
- -1.10 to -0.70
- -0.80 to -0.40
- -0.40 to 0.00
- 0.00 to 0.40
- 0.40 to 0.80
- 0.80 to 1.20
- 1.10 to 1.50
- 1.50 to 1.90
- 1.90 to 2.30
- 2.30 to 2.70
- 2.70 to 3.10
- 3.00 to 3.40
- > 3.40

TITLE **Bed Level Change Detection**
Waiho Loop to Mouth
Change in Bed Level 2016-2024
(84% Threshold)

Land River Sea
CONSULTING

AUTHOR	DATE	JOB CODE	REVISION	N
Rose Beagley	23 Feb 2024	WCRC039d	01	

4.1. SUB-REACH CHANGE ANALYSIS

4.1.1. CROSS-SECTIONAL CELLS ANALYSIS

For the 2019-2023 GCD analysis, the calculated mean bed level and volumetric change within cross-sectional cells is provided in Table 4-1. The longitudinal pattern of erosion and deposition, as well as a cumulative total volume change based on these units is also presented overleaf in Figure 4-1.

This analysis quantifies the downstream patterns of channel adjustment mapped in the GCD results maps and described in Section 4.2.

Table 4-1 – Summary of 2019-2023 GCD bed level and volume change (rounded to nearest 1000 m^3)

	Cross Section / Cells	Mean Bed Level (m)		Net volume (m^3)		Reach net volume change (m^3)
		Change	Error (m)	Change	Error (%)	
Upper Valley	XS0-XS1	-4.1	±0.23	-339,000	6	
	XS1-XS2	-1.2	±0.16	-210,000	14	
	XS2-XS3	0.7	±0.17	196,000	26	
	XS3-XS4	0.2	±0.16	17,000	118	
	XS4-XS5	-2.1	±0.24	-162,000	12	**-498,000**
Transport Reach	XS5-XS6	-0.5	±0.21	-28,000	43	
	XS6-XS7	0.5	±0.18	30,000	41	
	XS7-XS8	0.6	±0.19	36,000	33	
	XS8-XS9	1.3	±0.20	54,000	16	
	XS9-XS10	0.3	±0.17	9,000	67	**101,000**
Callery Confluence to End of Helipad Bank	XS10-XS11	-1.5	±0.27	-99,000	19	
	XS11-XS12	-0.9	±0.19	-32,000	21	
	XS12-XS13	-0.2	±0.18	-6,000	134	
	XS13-XS14	0.8	±0.22	25,000	27	
	XS14-XS15	1.1	±0.24	60,000	23	**-52,000**
End of Helipad Bank to Waiho Loop	XS15-XS16	1.1	±0.20	91,000	19	
	XS16-XS17	1.0	±0.20	275,000	20	
	XS17-XS18	0.9	±0.19	258,000	23	
	XS18-XS19	0.7	±0.19	103,000	25	
	XS19-XS20	0.6	±0.17	294,000	27	
	XS20-XS21	0.7	±0.18	373,000	27	
	XS21-XS22	0.4	±0.17	163,000	44	**1,557,000**
	XS22-XS23	0.8	±0.17	199,000	21	

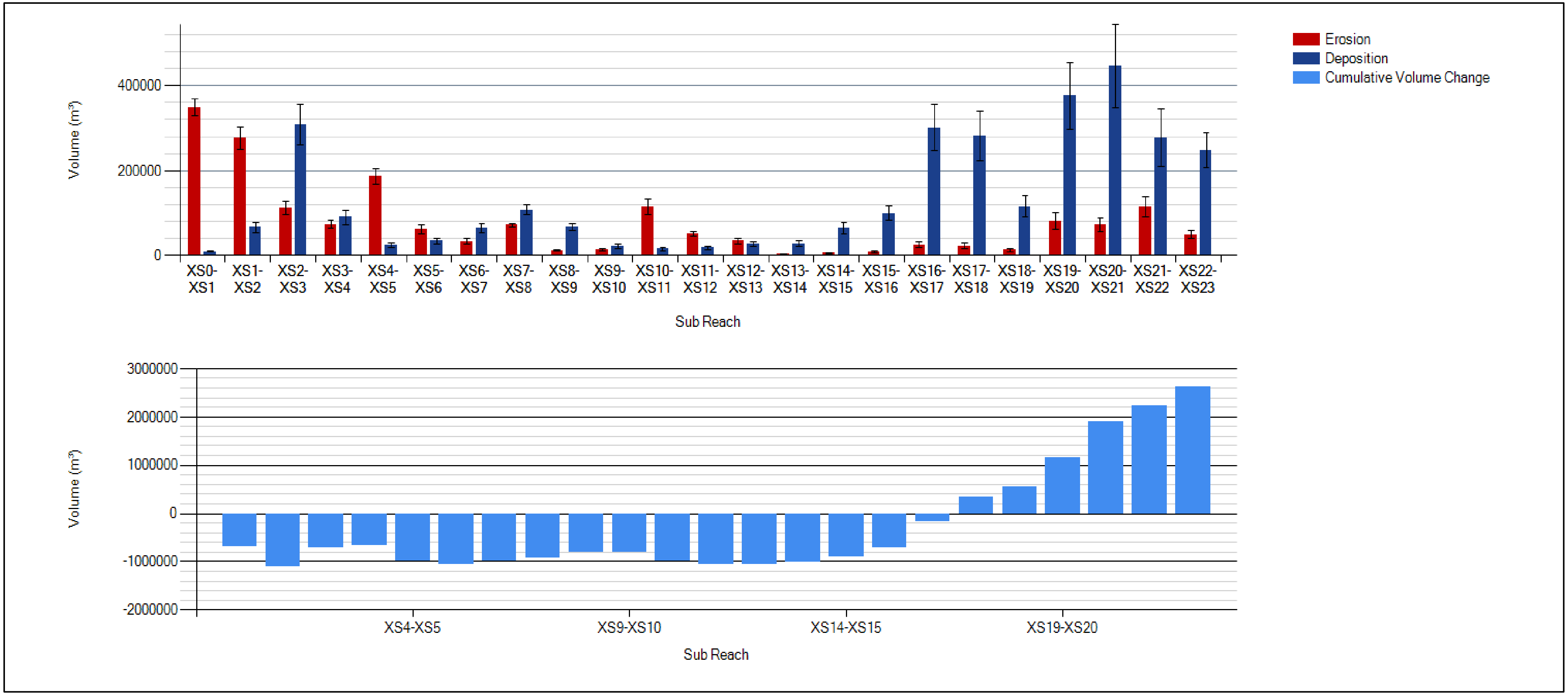


Figure 4-1 - 2019-2023 GCD summary of erosion and deposition and cumulative volume change between XS1 to XS23

For the 2023-2024 GCD analysis, the calculated mean bed level and volumetric change within cross-sectional cells is provided in Table 4-2. The longitudinal pattern of erosion and deposition, as well as a cumulative total volume change based on these units is also presented overleaf in Figure 4-2.

Table 4-2 – Summary of 2023-2024 GCD bed level and volume change (rounded to nearest 1000 m³)

	Cross Section / Cells	Mean Bed Level (m)		Net volume (m³)		Reach net volume change (m³)
		Change	Error (m)	Change	Error (%)	
Upper Valley	XS0-XS1	8.2	±0.28	804,000	3	
	XS1-XS2	2.8	±0.25	560,000	9	
	XS2-XS3	1.3	±0.21	308,000	17	
	XS3-XS4	0.5	±0.18	58,000	39	
	XS4-XS5	0.5	±0.19	30,000	41	**1,760,000**
Transport Reach	XS5-XS6	0.5	±0.22	26,000	46	
	XS6-XS7	0.8	±0.22	40,000	30	
	XS7-XS8	0.6	±0.28	21,000	46	
	XS8-XS9	0.9	±0.26	24,000	32	
	XS9-XS10	0.2	±0.17	7,000	76	**118,000**
Callery Confluence to End of Helipad Bank	XS10-XS11	-0.1	±0.14	-2,000	286	
	XS11-XS12	-0.8	±0.19	-8,000	23	
	XS12-XS13	0.2	±0.21	4,000	130	
	XS13-XS14	-0.1	±0.16	-1,000	198	
	XS14-XS15	-0.1	±0.16	-2,000	265	**-9,000**
End of Helipad Bank to Waiho Loop	XS15-XS16	-0.3	±0.20	-12,000	67	
	XS16-XS17	0.0	±0.17	-2,000	1732	
	XS17-XS18	0.4	±0.16	66,000	46	
	XS18-XS19	0.4	±0.18	33,000	51	
	XS19-XS20	0.1	±0.16	23,000	265	
	XS20-XS21	0.0	±0.13	-13,000	317	
	XS21-XS22	0.1	±0.15	28,000	153	**123,000**
	XS22-XS23	0.2	±0.16	29,000	85	

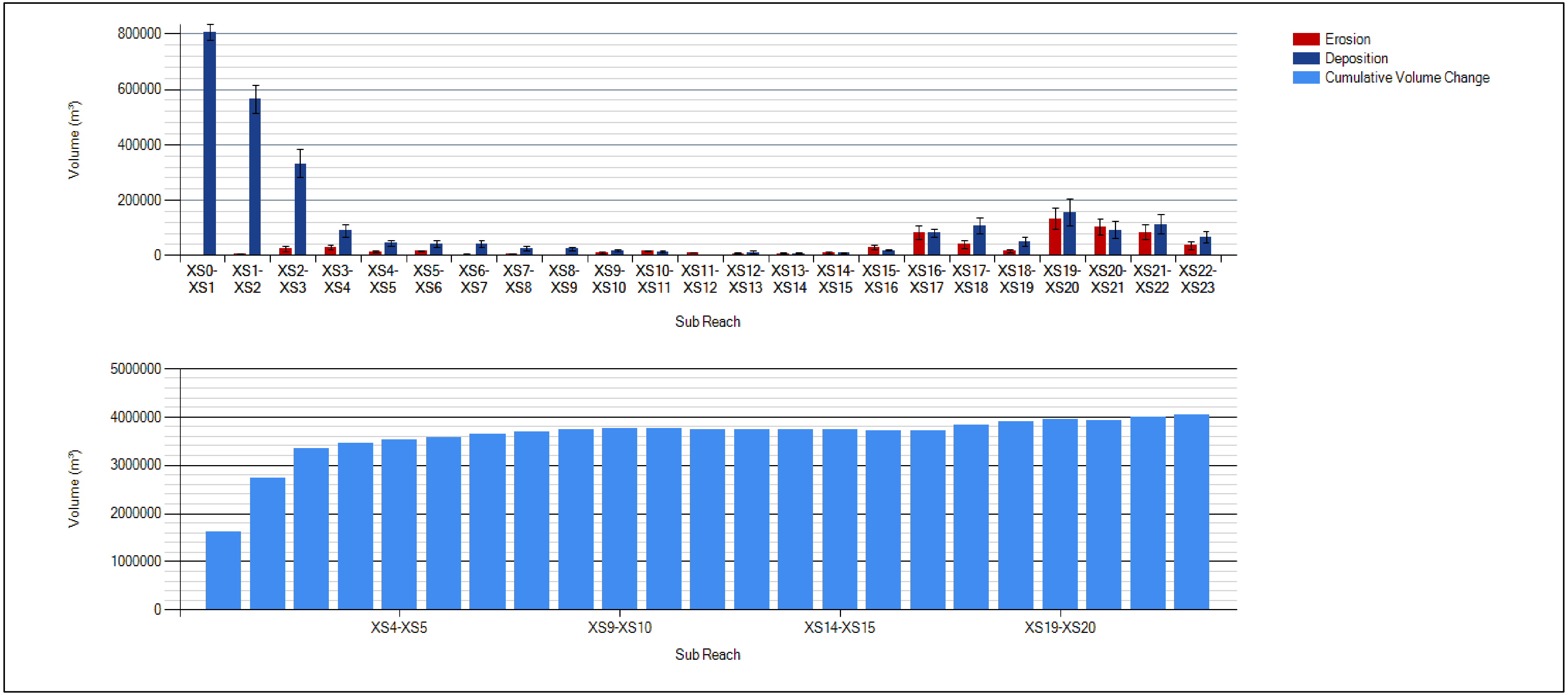


Figure 4-2 - 2023-2024 GCD summary of erosion and deposition and cumulative volume change between XS1 to XS23

4.1.2. CROSS-SECTION MEAN BED LEVEL ANALYSIS

To compare with historic cross-sectional survey data, a basic mean bed level analysis has also been carried out at each of the historic cross section survey locations.

Unlike the 2-dimensional analysis carried out using the LiDAR with the GCD tools, no adjustment has been made with the 2019, 2023 or 2024 datasets in order to account for the water surface for the cross-sectional analysis, so the results have a greater degree of uncertainty and will slightly overestimate the overall mean bed level for these surveys. However, considering the water surface only covers a small area of the active channel, the overall conclusions and trends are considered representative.

A summary of the changes in mean bed level from 1983 to 2024 is presented in Table 4-3 on the following page with plots showing the cumulative change from 1983 for each surveyed cross section presented in Appendix A.

Table 4-3 - Summary of Mean Bed Level based at historic cross section locations

	Mean Bed Level (m)														MBL Change (m)		
	1983	1990	1993	1999	2002	2008	2011	2012	2014	2015	2016	2019	2023	2024	2019 to 2023	2023 to 2024	1993 to 2024
XS1			245.5	253.0		253.1				250.7	250.6	253.8	250.3	256.2	-3.5	6.0	10.7
XS2	226.0	229.4	229.5	234.5		234.0				233.3	233.6	235.1	234.1	235.8	-0.9	1.7	6.2
XS3	212.8	214.0	214.6	216.3		216.4				217.2	217.3	217.6	217.6	217.9	0.0	0.3	3.3
XS4	205.2		206.8	207.8		207.6				207.8	207.5	208.6	208.8	209.1	0.2	0.3	2.3
XS5	195.8	196.1	196.0	195.9	195.9	195.7				196.0	196.3	198.4	196.2	196.1	-2.2	-0.1	0.1
XS6	185.4	185.3	184.9	185.3	185.3	184.7				185.4	185.0	186.8	186.3	187.0	-0.6	0.7	2.1
XS7	173.5	172.5	173.3	175.0	175.0	175.5				174.9	175.0	176.2	176.6	176.9	0.4	0.3	3.7
XS8	163.6	163.5	164.8	166.4	166.4	167.2				167.0	167.3	168.2	168.7	169.3	0.5	0.6	4.6
XS9	157.4	157.2	159.2	161.7	162.1	162.0				162.3	162.5	163.8	163.7	164.2	-0.1	0.5	5.0
XS10	152.8		154.2	158.0	158.0	158.3	160.2	160.1	159.5	159.4	159.4	159.6	159.5	159.6	-0.2	0.1	5.3
XS11	149.9	151.4	152.5	155.0	154.8	155.7	157.8	157.3	156.7	156.3	156.8	157.2	156.5	156.3	-0.7	-0.2	3.8
XS12			150.0	152.6	153.1	153.3	155.0	154.4	154.4	154.2	154.2	154.9	154.1	154.1	-0.9	0.0	4.1
XS13	145.7	145.1	145.9	148.9	148.4	149.1	150.6	150.0	150.5	149.9	150.5	150.5	150.5	150.2	0.0	-0.3	4.4
XS14			143.6	146.3	145.9	146.6	147.6	146.8	147.8	147.7	148.0	147.6	147.9	148.1	0.3	0.2	4.5
XS15			141.2	143.2	143.4	143.7	144.5	144.5	144.9	144.6	145.1	144.7	145.2	145.0	0.5	-0.2	3.8
XS16			137.7	139.2	139.6	139.8	140.2	140.2	140.5	140.5	140.9	140.9	141.4	142.5	0.5	1.1	4.9
XS17			133.1	134.3	134.4	134.6	135.2	135.2	135.6	135.7	136.0	136.2	136.5	136.7	0.3	0.2	3.6
XS18			127.8	128.7	128.9	129.2	129.7	129.7	129.8	129.8	130.1	130.7	131.0	131.1	0.2	0.1	3.3
XS19	123.6		124.0	124.3	124.6	124.8	125.2	125.3	125.2	125.3	125.6	126.5	126.6	127.0	0.1	0.4	3.0
XS20	116.9		117.1	117.4	117.4	117.9	118.3	118.4	118.5	118.8	118.7	119.1	117.7	117.0	-1.4	-0.7	-0.1
XS21	109.1		109.1	109.2	109.2	109.4	109.5	109.6	109.6	109.7	109.7	109.9	109.9	109.9	0.0	0.0	0.9
XS22	101.4		100.9	101.0	101.0	101.0	101.0	100.8	100.9	101.0	100.9	101.7	101.6	101.5	-0.1	-0.1	0.6
XS23	93.4		94.5	94.5	94.7	95.0	95.0	94.9	95.0	95.1	95.1	95.7	95.7	95.8	0.0	0.1	1.3

4.1.3. 500M CELLS ANALYSIS

A longitudinal analysis of volume changes was also undertaken along the entire length of the Waiho River, dividing the river into 500 m cells starting at the glacier and working downstream. In total the river is divided into 47 longitudinal budget cells, representing the full 23.5 km centreline length.

A summary for the 2019-2023 GCD analysis of the erosion and deposition changes for each of these units as well as a cumulative total volume change is provided in Figure 4-3 overleaf.

A summary for the 2023-2024 GCD analysis of the erosion and deposition changes for each of these units as well as a cumulative total volume change is provided in Figure 4-4 on page 34.

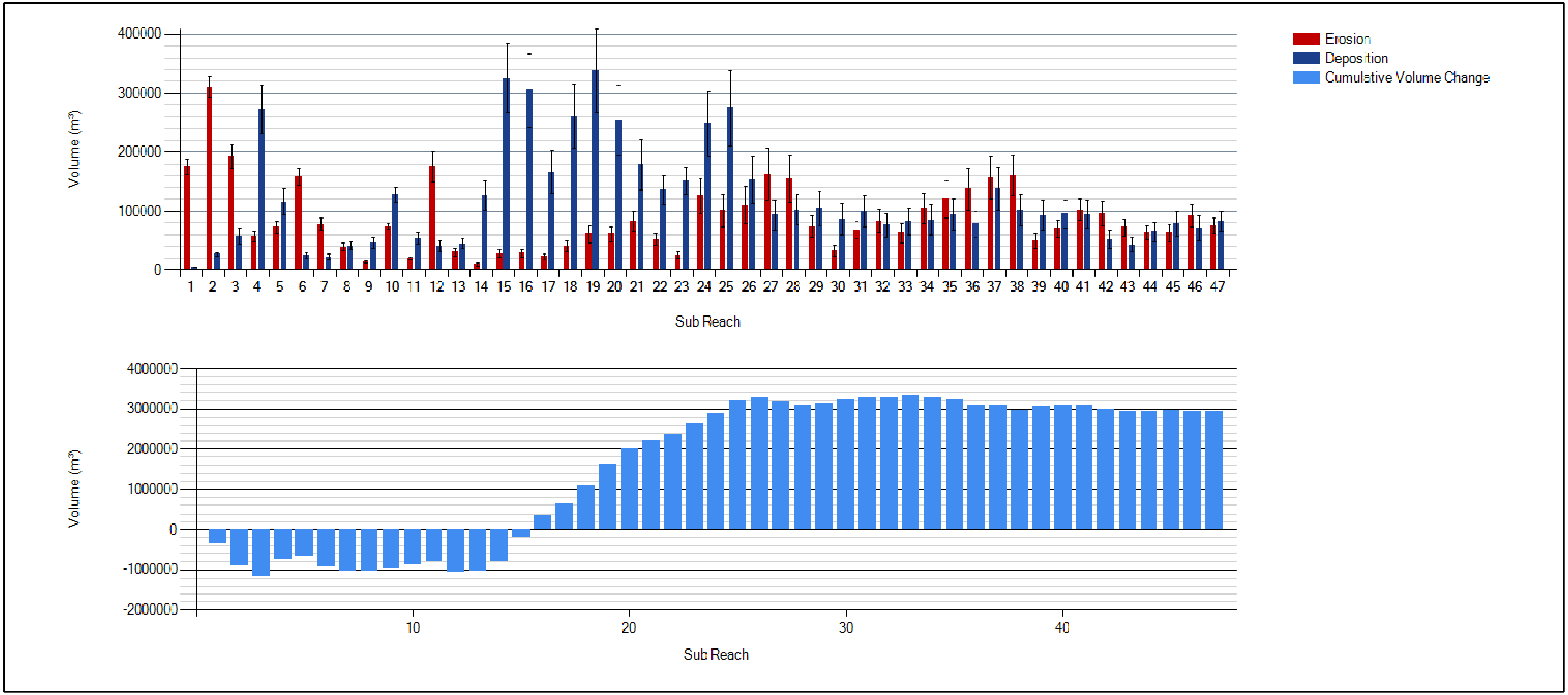


Figure 4-3 – 2019-2023 GCD summary of erosion and deposition and cumulative volume change for the entire Waiho based on 500 m cells

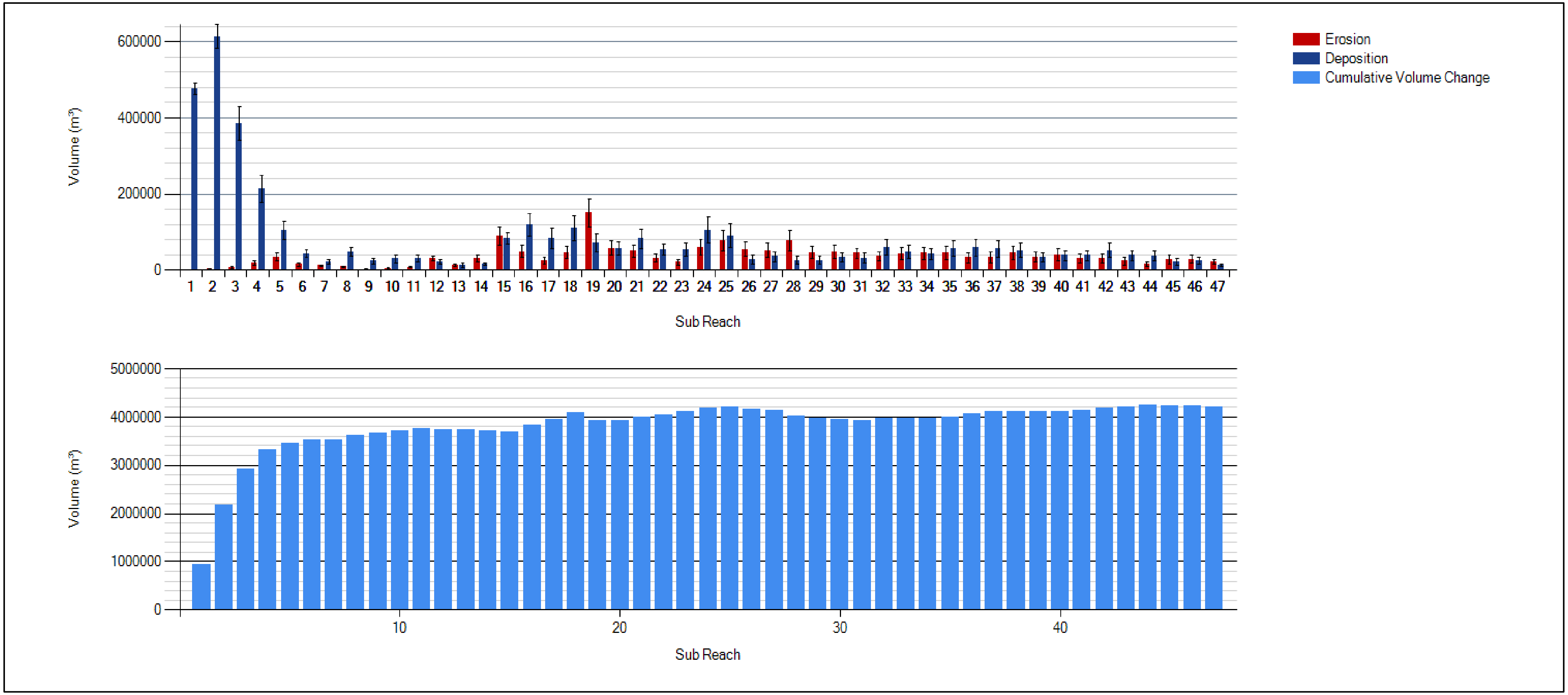


Figure 4-4 - 2023-2024 GCD summary of erosion and deposition and cumulative volume change for the entire Waiho based on 500 m cells

4.2. BROADSCALE PATTERNS OF BED-LEVEL CHANGE

4.2.1. WAIHO RIVER

The Waiho area of interest includes the entire active channel from the Franz Josef glacier terminus down to the Tasman Sea. As shown by all three GCD analyses (Table 4-4), this river experiences very large volumetric change (erosion and deposition), in the order of millions, at all four GCD time scales (7.5 months, and 3, 4 and 7.5 years).

Table 4-4 – Summary of volume differences within the Waiho AOI for each GCD analysis

	Volume Erosion (million m^3)	+\- Error (million m^3)	Volume Deposition (million m^3)	+\- Error (million m^3)	Net Volume Difference (million m^3)	Average Volume Difference (million m^3 per year)
2016 – 2019	3.68	0.88	6.68	1.54	**3.00**	1.00
June 2019 – June 2023	4.13	0.79	5.61	1.26	**1.48**	0.37
June 2023 – Jan 2024	1.67	0.57	3.85	0.81	**2.18**	3.49
2016 – 2024	3.60	0.87	10.76	2.07	**7.16**	0.95

The net volumetric difference for all four analyses show that, overall the river bed is experiencing long term aggradation, with a potential increase in rate of aggradation in the most recent survey period, although it is important to note that the short time period between surveys may result in an exaggeration of the annual rate of increase.

4.2.2. TATARE STREAM

The Tatare area of interest starts where the Tatare Stream exits the Southern Alps range-front and ends just downstream of the Waiho Loop where it joins the Waiho. The Tatare Stream shows greater variation between analyses than the Waiho (Table 4-5).

Table 4-5 - Summary of volume differences within the Tatare AOI for each GCD analysis

	Volume Erosion (million m^3)	+\- Error (million m^3)	Volume Deposition (million m^3)	+\- Error (million m^3)	Net Volume Difference (million m^3)	Average Volume Difference (million m^3 per year)
2016 – 2019	0.37	0.06	0.37	0.09	**0.01**	0.00
June 2019 – June 2023	0.44	0.08	0.08	0.02	**-0.36**	-0.09
June 2023 – Jan 2024	0.03	0.01	0.35	0.10	**0.32**	0.10
2016 – 2024	0.50	0.09	0.50	0.13	**0.00**	0

The net volume change fluctuates between all three possible states – relatively in balance (2016-19), degradational (2019-23) and aggradational (2023-24).

In the 2019-23 analysis, the -0.36 million m^3 net volume change is evident in the extensive bank erosion, and channel incision between the range front and Waiho Loop.

In the 2023-24 analysis, the aggradation is less a reflection of the state of the Tatare but rather the influence that the Waiho River is having through its avulsion into the Tatare Stream above the Waiho Loop. The 0.32 million m^3 of net volume change is for the most part a product of the sediment brought in by the Waiho depositing above, through and downstream of the Tatare cut in the Waiho Loop. The avulsion is discussed in detail in Section 4.3.5.

4.3. REACH-BASED CHANGE ANALYSIS

In this section, more detailed analysis of bed level change is provided at a reach-based scale with the inclusion of the avulsion area. This analysis has been based on the Waiho divided into separate reaches defined as the upper valley (XS0 – 5), transport reach (XS5 – 10), Callery confluence (XS10 – 15), fan (XS15 – 22) and valley train (cells 22 – 47) (Figure 4-5).

Figure 4-5 - Waiho reaches

Summaries of the mean bed level change and net volume change within each of these reaches across all four time periods / GCD analyses are provided in Table 4-6 to Table 4-10 below, and subsequent discussions in Section 4.3.1 to Section 4.3.6.

Table 4-6 – Upper valley: mean bed level change and net volume change

	Mean bed level change (m)	Net volume change (million m^3)
2016-19 (3 years)	1.38	1.10
2019-23 (4 years)	-1.28	-0.5
2023-24 (7.5 months)	2.61	1.76
2016 to 2024 (7.5 years)	2.50	2.37

Table 4-7 - Transport reach: mean bed level change and net volume change

	Mean bed level change (m)	Net volume change (million m^3)
2016-19 (3 years)	-0.30	-0.18
2019-23 (4 years)	0.40	0.10
2023-24 (7.5 months)	0.58	0.12
2016 to 2024 (7.5 years)	0.16	0.06

Table 4-8 – Callery confluence to helipad bank: mean bed level change and net volume change

	Mean bed level change (m)	Net volume change (million m^3)
2016-19 (3 years)	-0.18	-0.04
2019-23 (4 years)	-0.14	-0.05
2023-24 (7.5 months)	-0.18	-0.01
2016 to 2024 (7.5 years)	-0.35	-0.09

Table 4-9 - Waiho fan: mean bed level change and net volume change

	Mean bed level change (m)	Net volume change (million m^3)
2016-19 (3 years)	0.36	0.98
2019-23 (4 years)	0.76	1.56
2023-24 (7.5 months)	0.10	0.12
2016 to 2024 (7.5 years)	0.94	2.65

Table 4-10 – Valley train: mean bed level change and net volume change

	Mean bed level change (m)	Net volume change (million m^3)
2016-19 (3 years)	0.22	1.47
2019-23 (4 years)	0.07	0.36
2023-24 (7.5 months)	0.03	0.11
2016 to 2024 (7.5 years)	0.25	1.93

The volumetric change summarised by reach (including the avulsion extent) for each GCD analysis have been provided in Figure 4-6 overleaf.

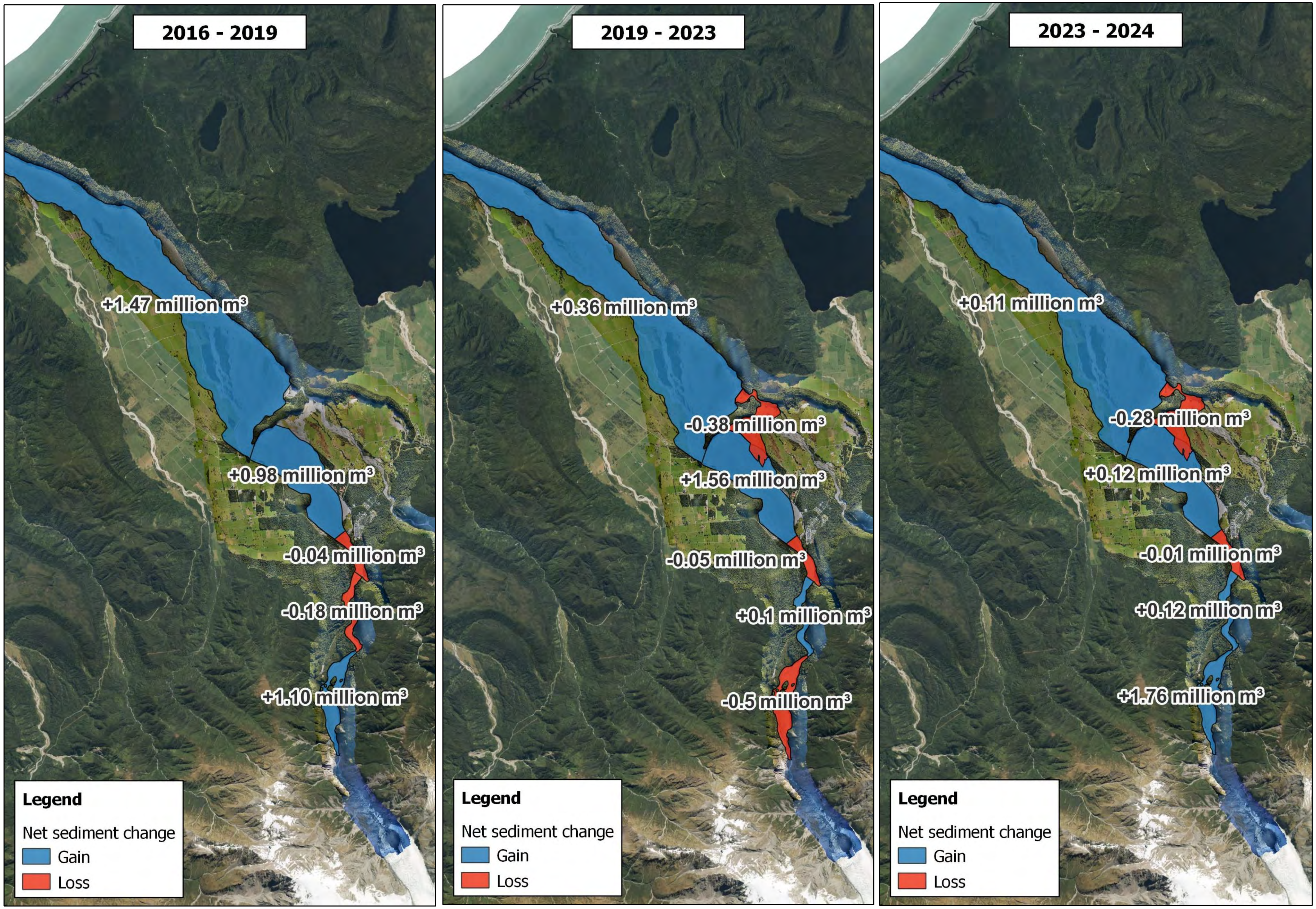


Figure 4-6 – GCD results summarised by reach for each of the three periods of analysis.

4.3.1. UPPER VALLEY

The 3.3 km long upper Waiho valley has undergone significant change between all four LiDAR surveys, capturing pronounced periods of aggradation and incision, which are indicative (perhaps at the extreme end) of the fluctuating nature of sediment movement through this reach.

Plots of cross-sectional data between 2016 and 2024 at 500 m and 1500 m from the upper extent of the LiDAR surveys – locations shown in Figure 4-7 – are provided in Figure 4-8 and Figure 4-9, respectively.

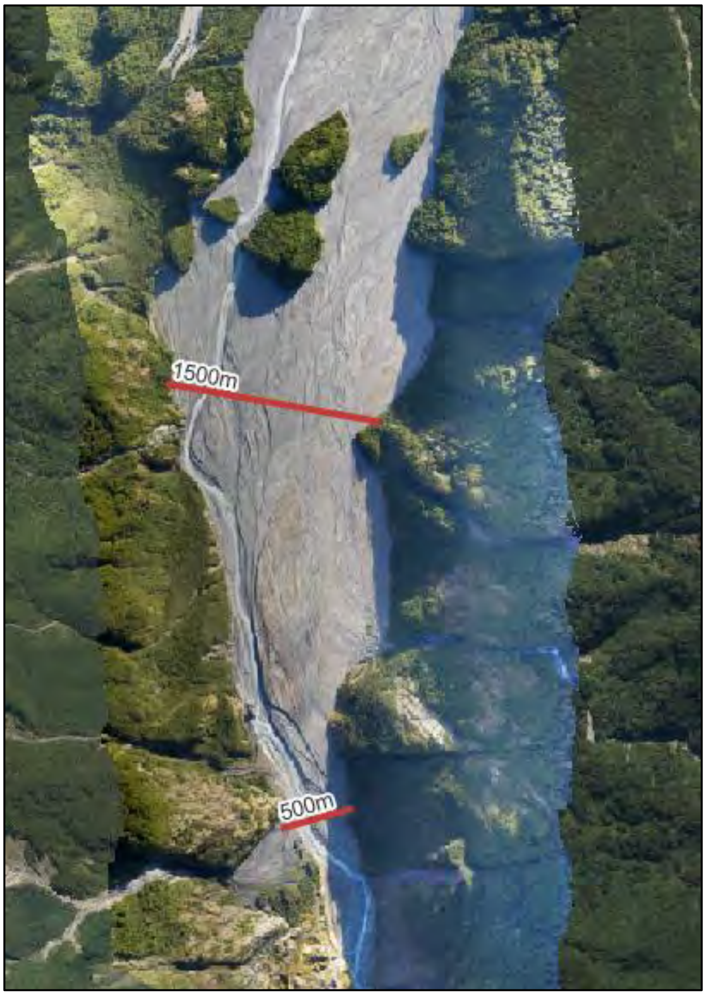


Figure 4-7 – Locations of cross-sectional profiles

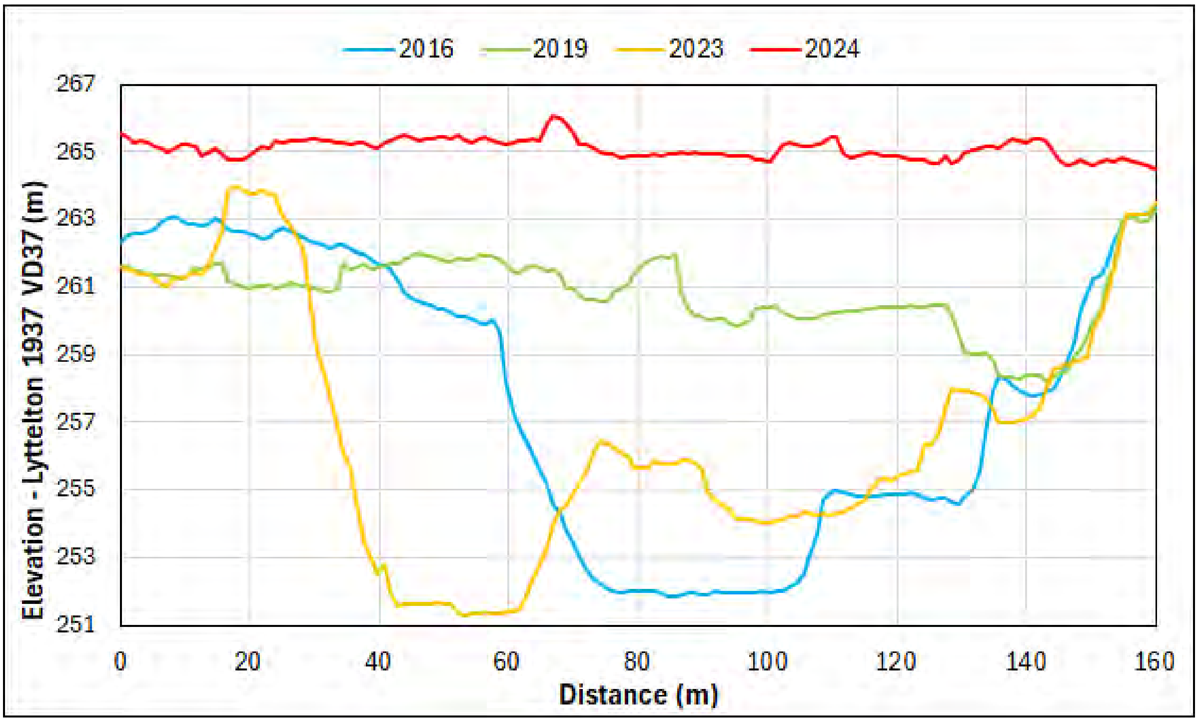


Figure 4-8 – Cross section 500m downstream from the upper extent of the LiDAR surveys.

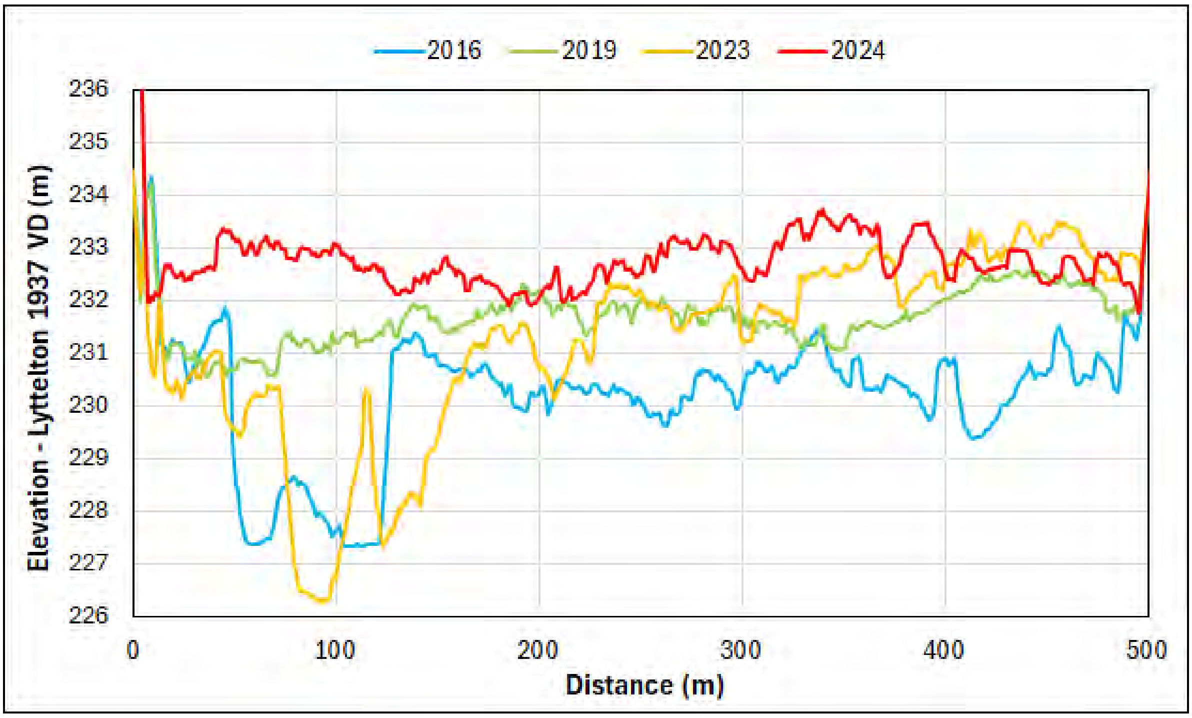


Figure 4-9 – Cross section 1,500m downstream from the upper extent of the LiDAR surveys.

These cross-sectional plots show these distinct changes in volume as the river alternates between deep incision (2016 and 2023) and massive aggradation between (2019 and 2024). Short term fluctuations are a result of the episodic nature sediment supply, with sudden aggradation likely due to weather events, and then incision as the river cuts back down between events.

Incision

- The 2016 and 2023 LiDAR surveys have captured degradational phases in this valley, where the main river channel has incised deeply into the valley floor. The 2016 and 2023 DEMs show the channel to be up to ~10 m deep in places in the upper part of the valley. With the 2019-23 GCD analysis showing a net volume loss of 0.5 million m^3 of sediment.

Aggradation

- In March 2019 and January 2024, multiday weather events triggered significant supplies of sediment into the upper Waiho valley. The 2016-19 and 2023-24 GCD results show that the valley floor aggraded by approximately 1.10 million and 1.76 million m^3, respectively, following these events. This amounts to an average vertical increase in bed level of approximately 1.38 m and 2.61 m across the entire valley floor, respectively.
- Live streamed photos from a fixed camera operated for the Franz Josef Glacier Guides and Department of Conservation (DoC) provide valuable insight into how the bed level can change drastically as a result of weather events. Imagery of the upper valley before and after the prolonged 6-day double event in January 2024 show the sudden increase in bed level Figure 4-10 and Figure 4-11 as captured by the 2023-24 GCD analysis. Of note, hydrological analysis (Section 6.2) indicates that this event was considerably smaller than that of the 2019 March event which produced a similar sized sediment pulse.

Figure 4-10 – Fixed camera 6 images from before and after the January 2024 event. The orange lines have been added for reference.

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Figure 4-11 - Fixed camera 7 images from before and after the January 2024 event. The orange lines have been added for reference, and the 500 m XS discussed above has been marked by the red dashed line.

Figure 4-12 – Fixed camera 8 images from before and after the January 2024 event with the 1500 m XS discussed above marked by the red dashed line.

Despite these periods of degradation shown by the 2016 and 2023 LiDAR surveys, cross sections surveyed since 1983 show that the general long-term trend is one of aggradation – see plots of XS1 to XS4 in Appendix A.

The infrequency of LiDAR and cross-section surveys makes it difficult to determine the rate at which sediment exits the upper valley and impacts downstream fan aggradation and requires additional data collection. Ongoing monitoring of the fixed camera imagery will assist understanding of sediment pulse frequency, incision rates, and the potential relationship between pulse magnitude and fan aggradation (noting that this excludes sediment supply from the Callery).

4.3.2. TRANSPORT REACH

The 2.7 km stretch of river between the downstream end of the upper Waiho valley and the confluence with the Callery is the narrowest reach along the main Waiho stem.

Mean bed levels from cross sections 7 to 9 show a general increasing trend within this reach (on average 0.1 to 0.2 m per year), with slightly larger increases in the 90s and since 2016 (see appendix A) which corresponds with the upper valley cross section MBL changes. The 2019-23 and 2023-24 GCD results also support this increasing trend, with the reach undergoing a net volume change of 0.10 million m^3 between 2019 and 2023, and 0.12 million m^3 between 2023 and 2024, and average vertical bed level changes of 0.13 and 0.93 m per year, respectively.

Whilst the bed is slowly aggrading through this reach, it is also being actively widened, with each GCD analysis showing progressive erosion of banks which is providing additional sediment supply to that coming from the valley above. The most notable bank failure occurred across a 250 m stretch along the Glacier Access Road between 2016 and 2019, as commented by Gardner and Brasington (2019).

4.3.3. CALLERY CONFLUENCE TO CROSS SECTION 15

Like the upstream "transport" reach, this section of river between the Callery confluence and cross section 15 (adjacent to the heliport) is one of the narrower parts of the main Waiho River. Bed levels through this reach undergo short term fluctuations within a long term aggradational trend, as shown by the mean bed level plot of the SH6 bridge cross section which is surveyed by Waka Kotahi - NZTA at 6-monthly intervals (Figure 4-13).

These short-term fluctuations are perhaps an indication of the episodic nature of sediment delivery from the two upstream subcatchments - the 77 km^2 Waiho and the 92 km^2 Callery. A fixed camera similar to what is located in the Upper Waiho valley could be installed looking upstream towards the riverbed beneath the Callery bridge so as to provide an indication of the frequency of sediment pulses from the Callery, and if there is a relationship between these and the short-term fluctuations in bed level in this reach.

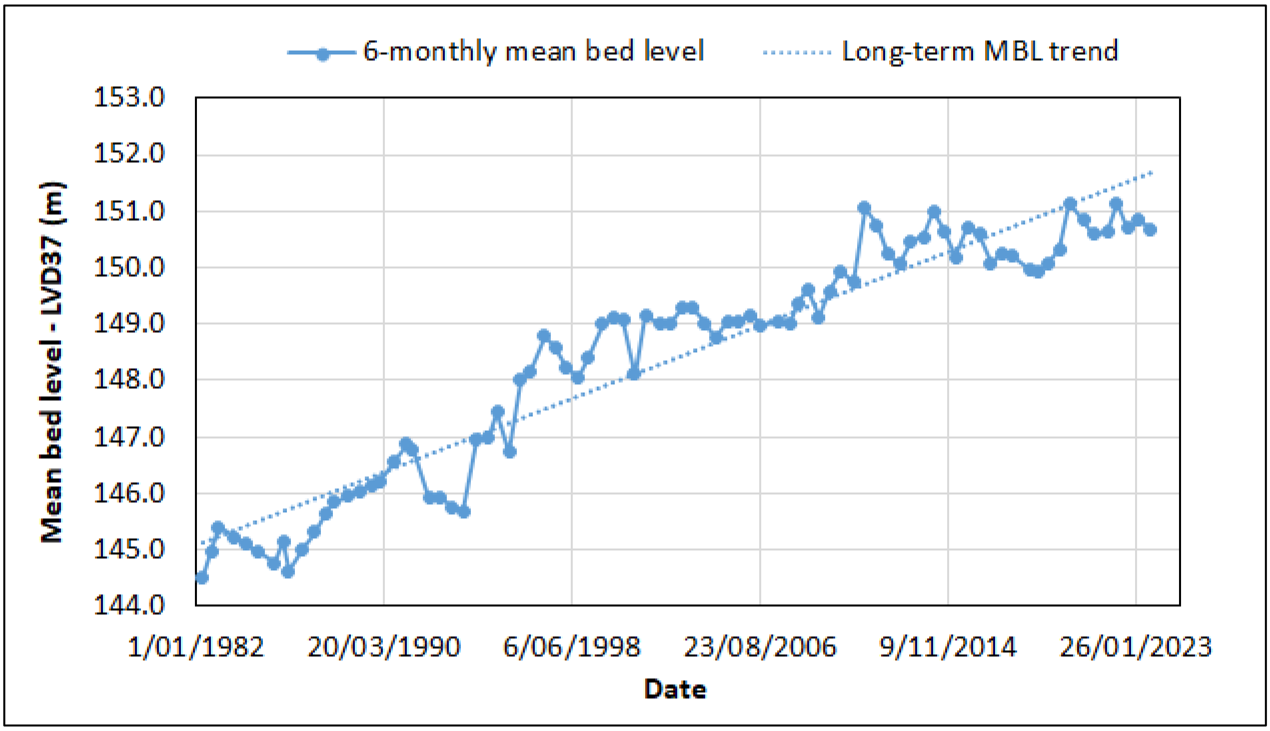

Figure 4-13 – Mean bed levels (MBL) survey at 6-monthly intervals at the SH6 Bridge cross section. Data provided by WSP – Waka Kotahi.

Despite the long-term aggradation trend at the SH6 bridge, all three GCD analyses and MBL plots from cross sections 11 to 13 (Appendix A), have captured degradational phases in this reach, with each analysis showing a net loss of sediment, albeit at a very small scale relative to the rest of the Waiho (0.01 to 0.05 million m^3; Table 4-8).

It is important to reinforce here that whilst a short term trend of degradation has been captured in recent surveys at this locations, it is very evident from inspection of the long term mean bed level recordings at the State Highway 6 bridge as well as the cross-section surveys which go back to 1993 in this reach indicate that this is not uncommon behaviour for this reach, where the bed levels appear to stay relatively stable for a decade or so at a time and then rapidly increase over several years. The long-term trend for this reach is very clearly aggradational.

However, inspection of each DEM of difference reveals that this net loss of sediment is largely attributed to erosion of the true right bank just downstream of the confluence (all three GCDs), as well as an incised channel extending downstream from the Callery (2019-23), and incised channels downstream of the SH6 bridge (2016-19) which are indicative of the intense scour which took out the bridge in the March 2019 event, and have since filled in. A comparison of the 2016, 2019, 2023, and 2024 LiDAR elevation data at a cross section 400 m downstream of the SH6 bridge shows that even with this net degradation, the Waiho River remains elevated several metres higher than the land to either of side it (Figure 4-14).

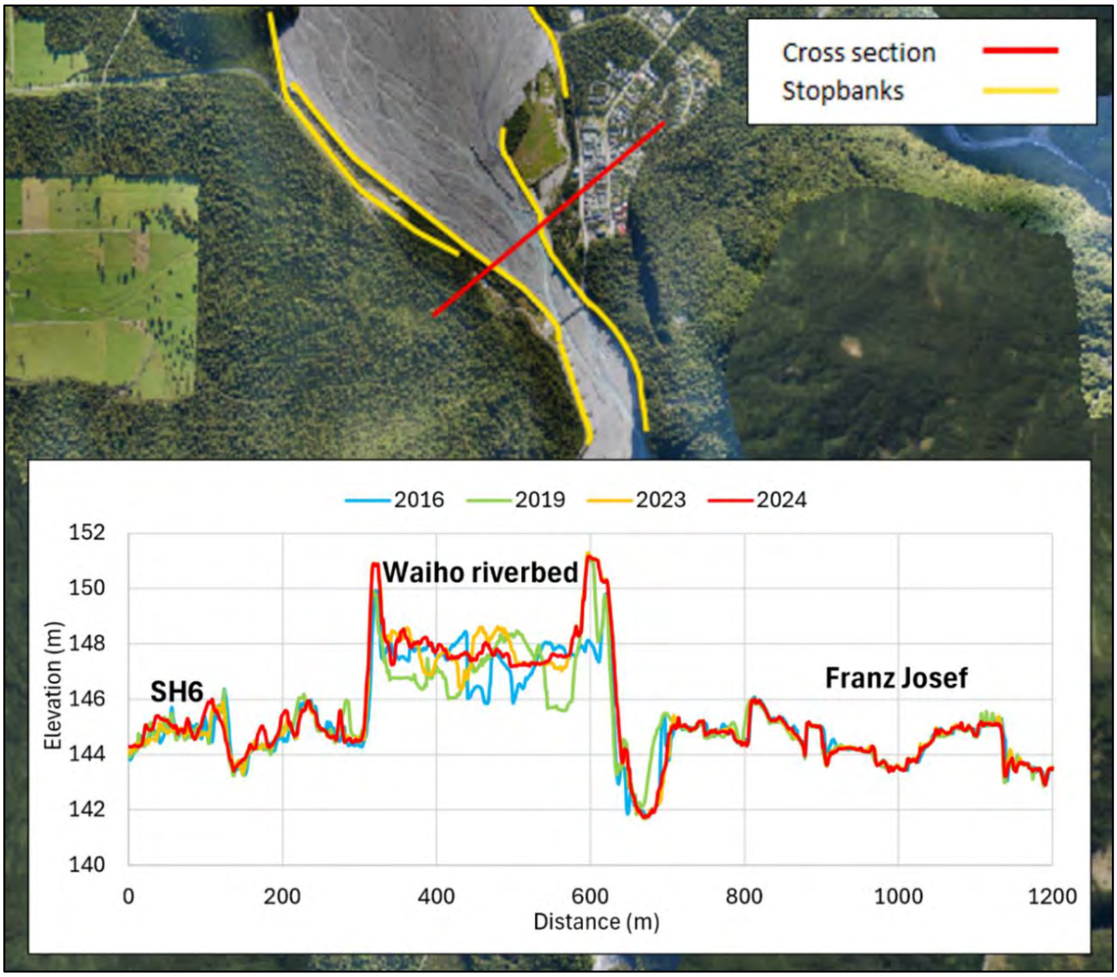

Figure 4-14 – Comparison of 2016, 2019, 2023 and 2024 elevation data at a cross section of the Waiho river bed 400m downstream of the SH6 bridge.

4.3.4. WAIHO FAN (HELIPAD BANK TO WAIHO LOOP)

The Waiho fan between cross section 15 and the Waiho Loop has been aggrading since the 1990's, as shown by the cumulative mean bed level plots (XS15 to 21, excluding XS20 – discussed below) in Appendix A. The GCD analyses support this trend, with mean bed levels and net volume change through this reach increasing in each analysis (Table 4-9).

This ongoing aggradation has led to the Waiho fan surface reaching a similar elevation to that of the Tatare fan surface, which has allowed the Waiho to spill over into the Tatare above the Waiho Loop. As the Waiho has begun to carve out a channel into the Tatare, it has incised down into its own bed, which has actually drawn the MBL at XS20 down in both 2023 and 2024 to below the MBL peak in 2019.

4.3.5. AVULSION CHANNEL AND TATARE STREAM

The avulsion reach starts at the upper extent of incision on the Waiho fan surface and ends at the toe of the fan forming downstream of the Tatare cut in the Waiho Loop (Figure 3-4).

February 2023

In February 2023, a small to medium sized flood event resulted in the Waiho breaking out (avulsing) across the Tatare fan surface and establishing a channel into the Tatare Stream above the Waiho Loop. The 2019-23 GCD indicates that during this February event and over the next four months, up to the June 2023 LiDAR survey, 0.51 million m^3 of sediment was eroded as the avulsion path developed between the two rivers (Table 4-11).

Table 4-11 – 2019-23 and 2023-24 volume erosion and deposition, and net change, in the avulsion sub-reach AOI.

	Volume Erosion (million m^3)	+\- Error (million m^3)	Volume Deposition (million m^3)	+\- Error (million m^3)	Net Volume Difference (million m^3)
2019-23	0.51	±0.07	0.13	±0.03	-0.38
2023-24	0.70	±0.09	0.42	±0.10	-0.28

During this time there was only 0.13 million m^3 of deposition between the top of the avulsion channel and just downstream of the Tatare cut in the Loop. Presumably in that initial February weather event, a lot of the finer sediment that makes up the Tatare fan surface (compared to that of the Waiho fan) was flushed through the Loop by the high discharge of a combined Waiho-Tatare and onto the longitudinal valley train to the sea. Then, because the main channel of the Waiho wasn't flowing down the avulsion during the months leading up to the June 2023 LiDAR survey there wasn't as much deposition compared to what is shown in the 2023-24 GCD analysis after the avulsion channel had experienced 95 % of the Waiho's flow and further deepening and widening (Table 4-5 and Figure 4-9).

January 2024

In January 2024, the avulsion underwent rapid development during a similar sized weather event to February 2023.

- The avulsion channel deepened and widened, and the incision point in the Waiho fan surface extended upstream towards the Treatment Ponds by approximately 500 m (Figure 4-15) as around 0.7 million m^3 of sediment was eroded by an estimated 95% of the Waiho River flow.
- A fan began to form at the downstream end of the channel where it joins the Tatare (and just above the cut through the Loop) and another just downstream of the cut in the Loop. Due to the deep water flowing through these two areas and the cut itself, there is greater uncertainty in the 0.42 million m^3 estimate of sediment deposition.

This greater volume of erosion down the avulsion channel to that of downstream deposition is indicative of the high stream power through the avulsion reach (steep gradient and large Waiho discharge) and therefore it's capacity to erode the finer sediment in the Tatare fan surface.

Additionally, between the 2023 and 2024 surveys, the point of incision at the top of the avulsion channel has migrated rapidly (~500 m) upstream towards the Treatment Ponds. This incision point acts like a knickpoint in the Waiho's longitudinal profile as it marks a distinct discontinuity in the bed elevation and slope, as the avulsion channel is at a much steeper grade to the main Waiho fan surface. Therefore, this upstream progression will continue (in addition to the downstream deposition in the Tatare) as the Waiho adjusts its form to create a smooth longitudinal profile through this reach (and down to the fan forming downstream of the Tatare cut in the Waiho Loop).

At the moment the rate that the incision is progressing upstream is occurring faster than the deposition in the Tatare as shown by the ratio of erosion to deposition in both the 2019-23 and 2023-24 analyses (Table 4-11). This is also evident in the long section plot through the avulsion comparing the 2019, 2023 and 2024 bed elevations. Figure 4-16 shows how the river in the 2024 DEM has incised down past the 2019 and 2023 bed surfaces between 400 and 2000 m along the long profile, and then only between 2140 and 2500 m has it begun to aggrade higher than the previous year's surfaces. Based on the current rate at which the incision point is migrating upstream, it could reach the treatment ponds within a year, however, it is unlikely to stop there. Depending on how fast the downstream end of the avulsion aggrades (a product of both the Waiho and Tatare borne sediment) progression could continue upstream with consequence for the Link bank, heliport, SH6 Bridge, and potentially the Franz Josef township.

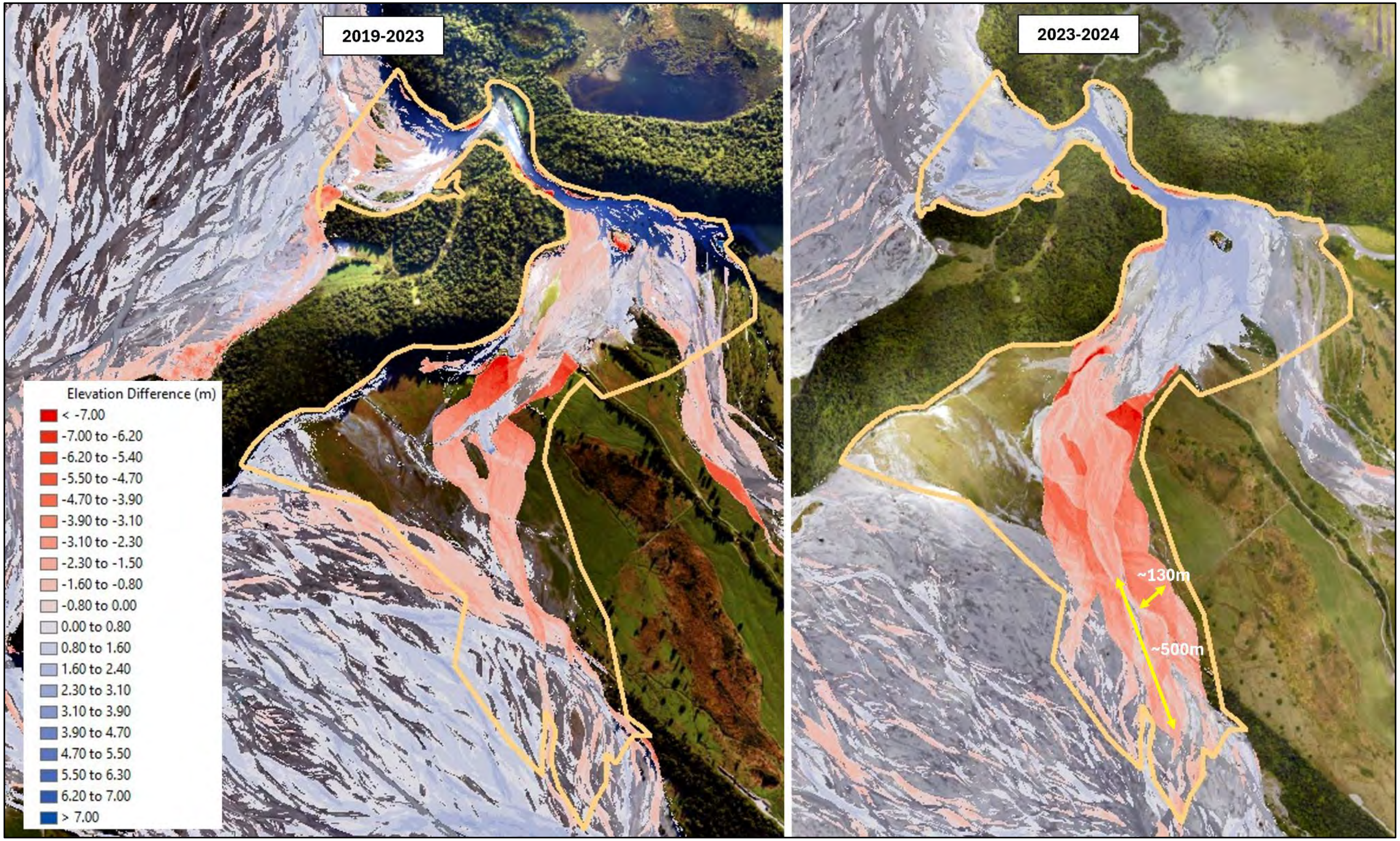

Figure 4-15 – Comparison of the 2019-23 and 2023-24 GCD DEMs of difference in the avulsion sub-reach, with yellow arrows used to indicate the lateral erosion, and upstream migration of the incision.

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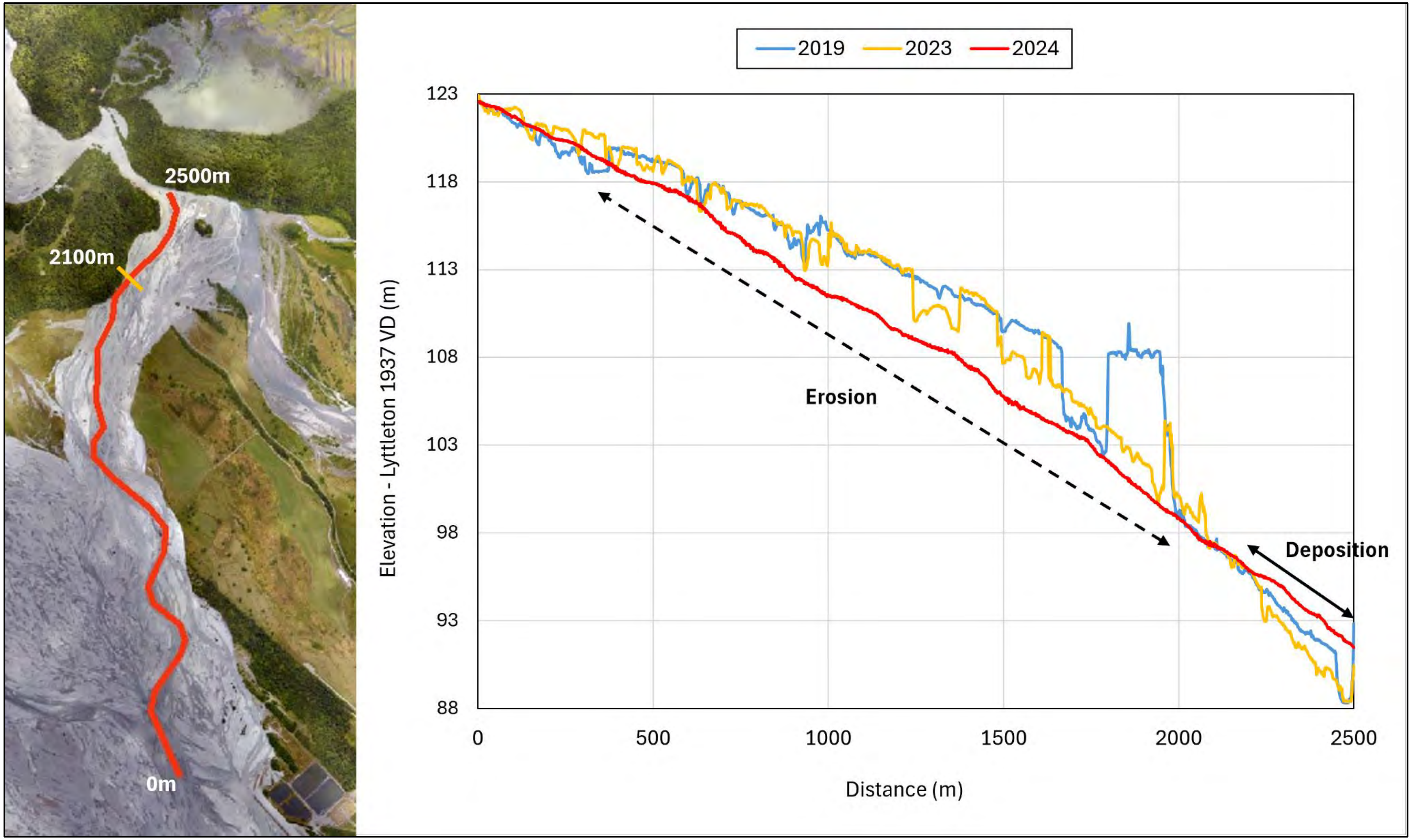

Figure 4-16 – Long section profile along the 2024 main channel down the avulsion, compared with the 2019 and 2023 elevation data. The orange line at 2100 m (on the image) marks the transition from erosion to deposition.

4.3.6. VALLEY TRAIN TO SEA

In the 2016-19 GCD analysis, this 13 km reach of river was net aggradational, with a net increase in sediment storage of 1.47 million m^3. Both the 2019-23 and 2023-24 analyses have followed this trend, recording net increases in sediment storage of 0.36 million and 0.12 million m^3, respectively; whilst exhibiting active reworking of the braidplain as shown by the abundance of change down this reach in the DEMs of difference figures.

Of note is the fact that the bulk of the material has been deposited in this reach between 2016 and 2019, potentially indicating that the 2019 event was a significantly larger event than other events in this period and had sufficient energy to transport sediment all the way down into this reach.

The increase in sediment volumes entering this reach is likely to result in increased pressure on adjacent farmland due to the river naturally wanting to increase in width in order to accommodate the increased sediment volumes within the river. This is already evident on site with the river already trying to increase in width and create new braids channels as shown in Figure 4-17.

Figure 4-17 – Photo of new braid channels forming downstream of the Waiho Loop (8/2/2024)

The 2023-24 analysis exhibits higher uncertainty in bed level and volume changes compared to prior analyses (2016-19, 2019-23). This is attributed to urgently requested data collection following a recent weather event whereby water levels were still high during the 2024 LiDAR survey.

5. DISCUSSION

5.1. WAIHO FAN AGGRADATION AND SHAPE

The GCD analyses and cross-sectional mean bed level plots show that the Waiho fan is in a long term aggradational trend, with the bed level increasing on average by 0.16 m per year. This trend is likely to continue at the current rate, if not faster, as sediment supply to the fan is likely to increase as a result of a warming climate and the transition into the positive phase of the sub Oscillation (IPO) increasing the intensity and frequency of flood events on the West Coast.

- Under all representative climate change pathways (RCPs; climate change projections) except 2.6, winter rainfall and flood flows increase in Westland prior to 2100 (Collins, 2021). Further, as the climate warms, there will be less snowfall and more rainfall than hitherto, meaning that storm runoff levels will increase (Beagley et al., 2023). Additionally, the increase in temperatures at high levels will lead to a reduction in rock faces reinforced by permafrost. This in turn will lead to an increase in the frequency of rockfalls and landslides, which causes increase in sediment supply to rivers.

- The IPO is believed to have switched to a positive phase around 2020, with fluctuations between positive, negative, and neutral phases since 2016 (Beagley et al., 2023). In a positive phase, New Zealand receives stronger west to southwest winds, which means that West Coast is wetter than average, experiencing more extreme rainfall and therefore more frequent and intense flooding than average (Griffiths et al., 2009; McKerchar & Henderson, 2003; Thompson, 2006; Wratt et al., 2022). The long-term record shows oscillations over decadal timescales (Figure 5-1).

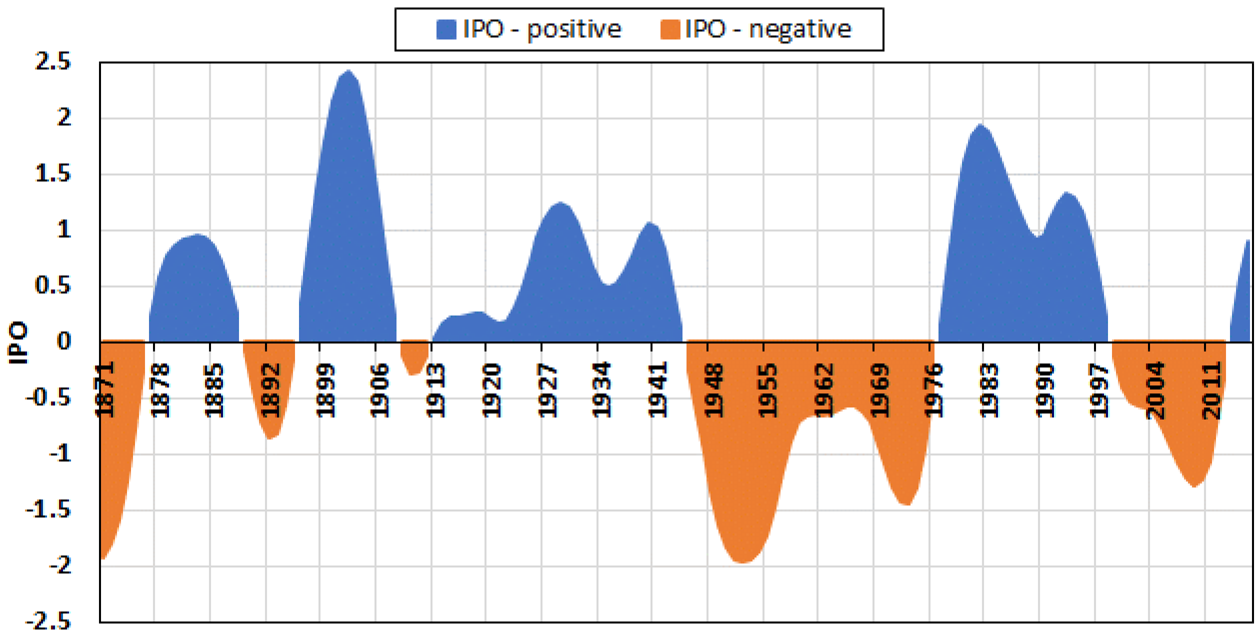

Figure 5-1 - Positive and negative phases of the IPO between 1871 and 2016.

As rainfall event intensity and frequency increase, so too will the mobilisation of sediment as well as the frequency of mass movement events such as shallow landslides (Jakob & Owens, 2021). This will result in an increase in both the volume of sediment entering river systems, and the frequency of these supply events.

As the fan surface continues to aggrade, the capacity of the stopbanks which confine the Waiho River through this reach will reduce and therefore will require ongoing upgrades if the level of service is to be maintained. Additionally increased channel activity across the fan surface as the river moves sediment across it, may lead to increased pressure on the stopbanks and therefore increase their likelihood of failure.

The aggradation has also been slowly changing the overall shape of the Waiho fan within the confines of the stopbanks. By overlaying aerial imagery from 2016, 2019, 2023 and 2024 with the 1 m and 5 m contours from the LiDAR surveys we have been able to identify the changing shape of the fan and the effect this is having on the main channel alignment and therefore the impact on the stopbanks and avulsion channel.

In each consecutive survey, as the fan aggrades (as shown in the GCD and MBL analyses) the true right side of the contours on the active riverbed begin to shift downstream.

- In 2016 and 2019, the general shape of these contours encourage the main channel to flow to the true left and down through the gap between Rata Knoll and the southern end of the Waiho Loop (Figure 5-2). This is largely due to the pronounced curvature of the contours in the lower part of the fan which funnels the flow to the left.
- In 2023, the contours on the true right downstream of Canavan's Knob have extended past those on the left, and created fall to the true right towards the Tatare fan (Figure 5-3). The curvature of the contours (across the entire lower fan) that serve to funnel flow to the left in 2016 and 2019, is no longer obvious. However, the main fall is still to the left, as highlighted by the main channel alignments extracted from the Sentinel Imagery (Figure 5-3).
- Additionally, throughout 2023, there was a temporary bund in front of the heliport stopbank and at times extending downstream of it, which encouraged the main channel to extend down the true left side of the river bed where it then deflected off (and on occasion wrapped around) Canavan's Knob before continuing down towards the Rata Knoll/Waiho Loop gap.
- In 2024, perhaps in response to the rapidly developing avulsion (as well as the fan surface aggradation), there has been a fundamental shift in the shape of the fan (Figure 5-3). From Canavan's Knob down, a majority of the flow is now directed towards the true right and into the avulsion channel.
- However, this will not prevent the main channel from flowing to the true left. The braided nature of the Waiho means it's constantly shifting sediment around and adjusting its channel alignment. In February 2024, the main channel switched back to the true left, wrapping around Canavan's Knob and then flowing down the true left and through the Rata Knoll and Waiho Loop gap, whilst still providing some flow down the avulsion channel.

The impact of this 2024 change in fan shape across the active riverbed is that in future it is more likely than in the past to encourage the main flow to the true right, which will further develop the avulsion and also facilitate the aggradation occurring along the true right active river bed between the downstream end of the Heliport stopbank and Canavan's Knob. This places increased pressure on the Heliport, Link and Havill's stopbanks. It may also place more pressure along the Rubbish Dump stopbank, as flow down the true left may tend to wrap around Canavan's Knob and run along this stopbank.

Figure 5-2 - July 2016 and April 2019 fan shapes shown by 1 and 5m contour lines.

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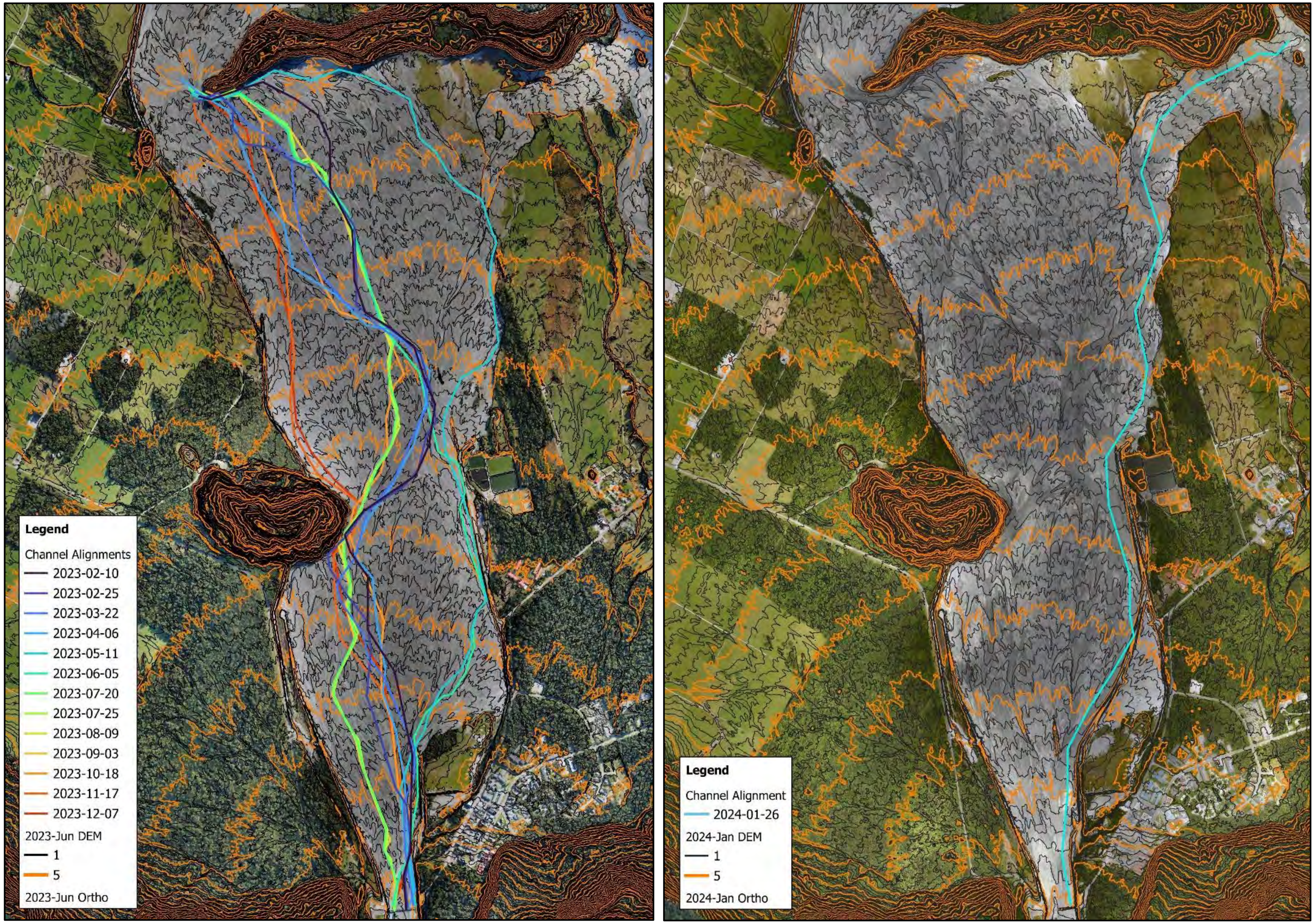

Figure 5-3 - June 2023 and January 2024 fan shapes shown by 1 and 5 m contour lines, with channel alignments taken from Sentinel satellite imagery.

5.2. AVULSION DEVELOPMENT

In early February 2023, a prolonged eight-day period of rainfall which included two different weather systems (Appendix C) resulted in the Waiho River partially avulsing into the Tatare Stream above the Waiho Loop. Around 0.51 million m^3 of farmland was eroded as the river carved out a channel down into the Tatare.

Over the next ten months, both monitoring sites recorded higher than the average monthly rainfall totals for March, April, May, September, and October (Appendix C) indicating that river levels were likely higher than normal throughout these months, which would have contributed to the portion of the Waiho which continued to flow down the avulsion channel during this time.

In January 2024, another prolonged period of rainfall (six days) also involving two weather system (Appendix C) resulted in 95% of the Waiho River flowing into the Tatare above the Loop, deepening and widening the avulsion channel.

Statistically neither of these events were particularly large in comparison to some of the significant events the area has experienced, as recorded by the Waiho Rv @ Douglas Hut rainfall monitoring site (Table 5-1). Some examples of larger (prolonged) events with significantly higher ARIs (Table 5-2) than the Jan and Feb avulsion events, for 1 to 6-day maximum rainfall totals include:

- December 1984: airstrip and hotel flooded on the true right.
- December 1995: SH6 bridge damaged.
- January 2013: Wanganui Rv SH6 bridge damaged.
- March 2019: SH6 bridge and Milton's stopbank destroyed.
- February 2022: no reported damage or at least known to these authors.

Table 5-1 – Maximum rainfall total ARIs for a range of durations recorded by the Waiho Rv at Douglas Hut site (1983 – 2024; Gumbel; calendar year).

Event	1hr	2hr	3hr	6hr	12hr	1 day	2 day	3 day	6 day
Feb-23	1.0	1.1	1.1	1.4	1.2	1.2	1.5	1.5	2.4
Jan-24	1.0	1.0	1.0	1.0	1.1	1.5	1.8	1.4	2.3

Table 5-2 – Maximum rainfall total ARIs for 1, 2, 3, and 6-day durations during some of the significant weather events on record at the Waiho Rv at Douglas Hut site (1983 – 2024; Gumbel; calendar year)

Event	1 day	2 day	3 day	6 day
Dec-1984	3.5	3.8	10.7	25.0
Dec-1995	12.6	65.1	35.2	21.6
Jan-2013	14.0	9.7	6.2	7.6
Mar-2019	8.2	18.1	9.4	4.5
Feb-2022	32.3	22.9	33.3	15.9

The ARIs recorded by the Douglas Hut site for the February 2023 and January 2024 are all between 1.0 and 2.4 years. These are not significant.

This indicates that the current elevation and shape of the fan is such that it didn't require a large/significant weather event (and therefore large flow) to trigger the start of the avulsion in February 2023 nor to rapidly accelerate it in January 2024. This is problematic for a number of reasons:

- Low recurrence interval events such as those in Feb 2023 and Jan 2024 are likely to occur once a year, or at least every two years.
- A warming climate and a transition into the positive phase of the IPO are likely to increase the frequency and intensity of flood events.

Therefore, weather event occurrence (and intensity) will continue at, if not increase from, the current frequency, which means that the avulsion is likely to continue to develop at its current pace if not faster when there is flow down it.

The implication of this development is that it is highly likely that within a year, the incision at the top of the avulsion channel will have migrated upstream to the Treatment Ponds, undermining them. The incision is also likely to continue to migrate upstream beyond the ponds, with consequences for the SH6 and bridge, Heliport, and potentially the Franz Josef township.

Additionally, increased flood event frequency and intensity is likely to lead to increased sediment supply, which will accelerate the deposition occurring in the Tatare at the downstream end of the avulsion, and the backfilling up towards the Tatare SH6 bridge. Davies (2024) has calculated how long it may take for this backfilling to occur.

- The Tatare valley between the rangefront and Waiho Loop has a surface area of around 1 million m^3 with an average depth of about 5 m, giving a volume of around 5 million m^3.
- Based on its catchment area and the average annual uplift, annual sediment supply from the Tatare catchment is around 0.28 million m^3 per year.

At this supply rate, Davies (2024) has estimated that the Tatare valley could be infilled in about two decades. However, the Tatare SH6 bridge is likely to be threatened by the rising river bed sooner than this, perhaps within a decade.

Morphological modelling would provide greater certainty on how the avulsion will develop including the upstream progression of the incision point, and infilling of the Tatare valley.

6. CONCLUSIONS

Four LiDAR surveys have been conducted of the Waiho River in 2016, 2019, 2023 and 2024, allowing for a detailed comparison of each dataset to be undertaken. Analysing these surveys in conjunction with the historic cross section survey data adds valuable perspective to the ever changing riverscape.

The following conclusions can be drawn from the analysis discussed in this report:

BROAD SCALE ANALYSIS

- Analysis shows that whilst the rates of deposition fluctuate from year to year and are likely event based, the trend is strongly depositional, with 7.16 million m^3 accumulating within the Waiho River system between June 2016 and January 2024 averaging at a rate of 0.95 million m^3 per year.
- Rates of aggradation between June 2023 and January 2024 are approximately double the long-term average rates with 2.18 m^3 depositing over this 7.5 month time period equating to a rate of 3.49 million m^3 per year (the majority of this buildup is in the Upper Valley however). It is important to note that the short time period between surveys may result in an exaggeration of the annual rate of increase as deposition is likely strongly linked to specific weather events noting that in the 2019 to 2023 periods, the rates of deposition were only 0.37 million m^3 per year.
- Analysis of the Tatare Stream shows fluctuation between periods of erosion and deposition, although over the 2016 to 2024 period it is showing as more or less to be in equilibrium. However, this has been influenced in the past year by an influx in sediment from the Waiho River via the avulsion. This build-up of sediment at the Tatare Cut has the potential to disrupt sediment transport through the Tatare Cut, potentially causing the sediment to back up and hence cause the bed levels in the stream to aggrade over time.

REACH BASED ANALYSIS

Upper Valley

- There is a strong overall aggradational trend in the Upper Valley over the 2016 to 2024 period, however this has fluctuated between aggradational and degradational phases.
- In total, 2.37 million m^3 has deposited in this reach since 2016, however 1.76 million m^3 of this has been deposited in the period from June 2023 to Jan 2024.
- Following significant deposition between 2019 and 2023, there was a period of degradation with 0.5 million m^3 being lost from the reach.
- Short term fluctuations are a result of the episodic nature of sediment supply, with sudden aggradation likely due to weather events, and then incision as the river cuts back down between events.
- Fixed camera imagery indicates that the January 2024 event was the principal driver of this 2024 sediment supply, and it is likely that the March 2019 event (statistically bigger) was also a principal driver of the 2019 supply.

Transport Reach

- Apart from a period of degradation from 2016 to 2019, this reach is showing as generally aggradational indicating supply is now exceeding its transport capacity.
- Whilst the bed is slowly aggrading through this reach, it is also being actively widened, with each GCD analysis showing progressive erosion of banks which is providing additional sediment supply to that coming from the valley above.
- Analysis of the cross-section surveys in this reach indicate that a similar bed level trend last occurred around the 1990's which also corresponds to a positive IPO cycle when sediment supply generally increases.

Callery Confluence to Helipad Bank

- This reach is showing as slightly degradational over the entire period from 2016 to 2024 as well as for each survey period.
- Inspection of the long term mean bed level recordings at the State Highway 6 bridge as well as the cross-section surveys which go back to 1993 in this reach indicate that this is not uncommon behaviour for this reach, where the bed levels appear to stay relatively stable for a decade or so at a time and then rapidly increase over several years. It is very clear from historic data that the long-term trend for this reach is aggradational.
- It is impossible to predict when bed levels will begin to increase again within this reach, however this will occur when the sediment supply from upstream exceeds the transport capacity.

Waiho Fan

- The Waiho Fan has aggraded over all survey periods with a total of 2.65 million m^3 accumulating on the fan over the 2016 to 2024 period.
- Comparison of the rates of aggradation on the fan indicate that the rate of aggradation is reasonably constant between the 2016-19 and 2019-23 analyses, whilst in the 2023-24 analysis, the rate has slightly decreased. This decrease is likely a reflection of the shorter time period (7.5 months compared to 3 and 4 years) and is likely to increase over the coming years by the increased volumes of sediment in the upper Waiho valley transferring downstream onto the fan.
- This ongoing aggradation has led to the Waiho fan surface reaching a similar elevation to that of the Tatare fan surface, which has allowed the Waiho to spill over into the Tatare upstream of the Waiho Loop.

Valley Train

- 1.93 million m^3 of material has deposited within this reach between the 2016 and 2024 surveys, with the majority of this material being deposited between 2016 and 2019, likely following the 2019 flood event.
- Increasing bed levels within this reach are likely to continue to put pressure on the adjacent farmland with the river wanting to naturally widen as volumes of sediment increase within the reach.

- The avulsion of the Waiho River into the Tatare River is a major event resulting in significant and rapid geomorphic change in the river systems.
- Two events in February 2023 and then in January 2024 have resulted in erosion in the order of 1.2 million m^3 with large volumes of deposition also remaining in the Tatare system (0.55 million m^3).
- Neither of these two events were statistically significant. The occurrence and rapid development of the avulsion is the result of the current fan setting and bed levels in the river.
- Analysis shows that the January 2024 event has resulted in significantly more erosion than the February 2023 event despite being of a similar size, indicating that the upstream migration of the avulsion channel is accelerating and is likely to continue to accelerate in future events due to the increased stream power from the steeper slope.
- The treatment ponds are now at imminent at risk of being undermined by the incision extending upstream from where the Waiho has cut (avulsed) into the Tatare fan and carved out a channel down into the Tatare Stream.
- In the 7.5 months between LiDAR surveys, this knickpoint (start of the incision) has migrated approximately 500 m towards the ponds, with only a further 500 m separation remaining to the ponds.
- At current rates of progression, we can expect the treatment ponds to be threatened within one year, however this is likely dependant on the magnitude and frequency of flood events.
- It is likely that the knickpoint will continue to migrate upstream past the treatment ponds which may impact the Heliport, SH6 and bridge, and potentially the Franz Josef township.
- The Waiho has now established a definite channel into the Tatare Stream upstream of the Loop, which it has widened and deepened since June 2023. It has also started to deposit sediment immediately upstream, in, and downstream of the Tatare cut in the Waiho Loop.
- There is potential for both Tatare and Waiho borne sediment to infill the Tatare Stream towards the SH6 bridge. The rate of this infilling will depend on the frequency and intensity of weather events and therefore sediment supply.
- The fan forming immediately downstream of the Tatare cut in the Loop may serve to push water to the true left, potentially increasing erosion along the true left bank below the Waiho Loop.
- Morphological modelling would provide greater certainty on how the avulsion will develop including the upstream progression of the incision point, and infilling of the Tatare valley.

GENERAL

- No information on sediment volumes is currently collected in the Callery subcatchment which makes up a significant proportion of the overall Waiho catchment. Fixed camera imagery looking upstream at the Callery bridge may provide some insight into sediment supply from this river, at a relatively low cost.

- A warming climate and a transition into the positive phase of the Interdecadal Pacific Oscillation is likely leading to increased weather event frequency and rainfall intensities, and as a result increased sedimentation from both the Callery and Upper Waiho subcatchments.
- Aggradation on the fan is likely to continue and may lead to increased pressure on the existing stopbanks. The Havill Wall stopbank is likely to be under significant pressure, but the true left stopbanks including the unlined section of the Rubbish Dump stopbank and the Milton's and others bank are likely to be under increased pressure as the fan continues to aggrade.

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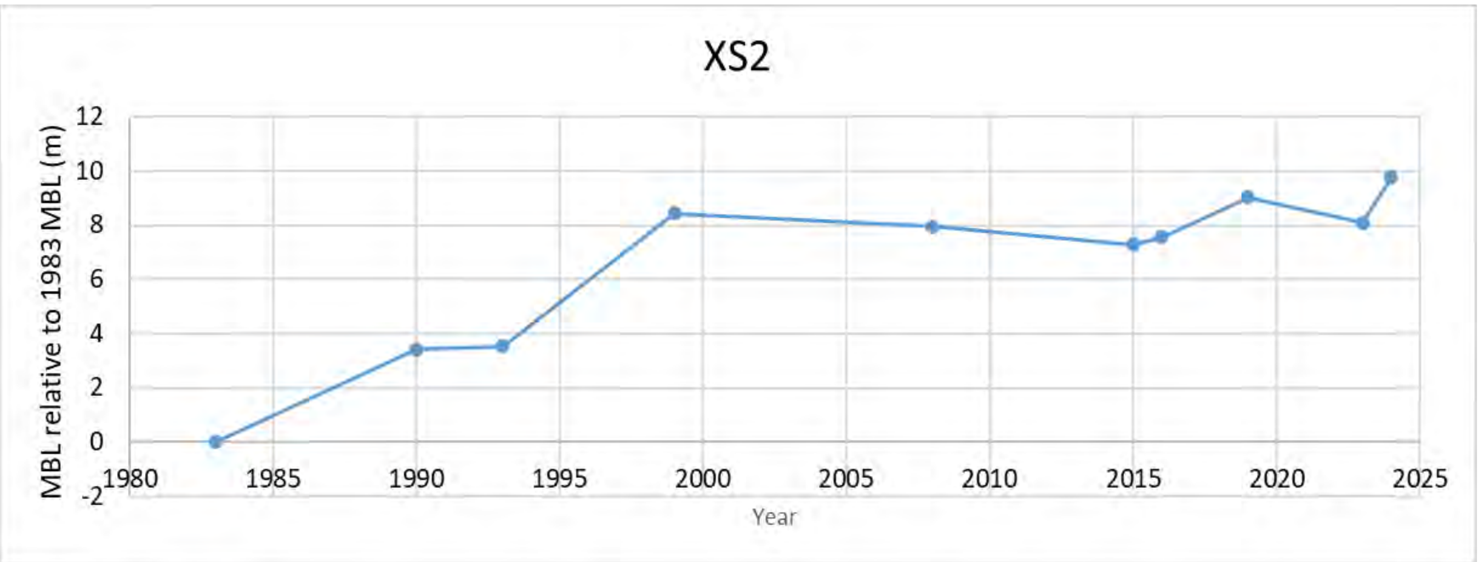
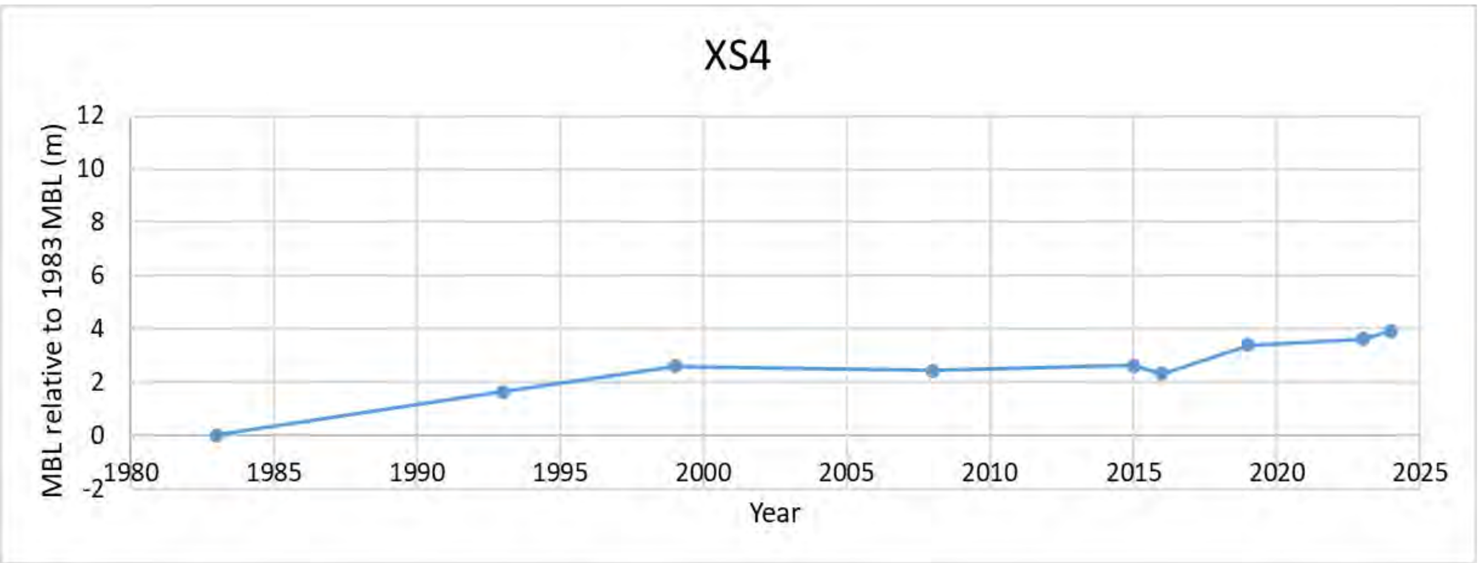
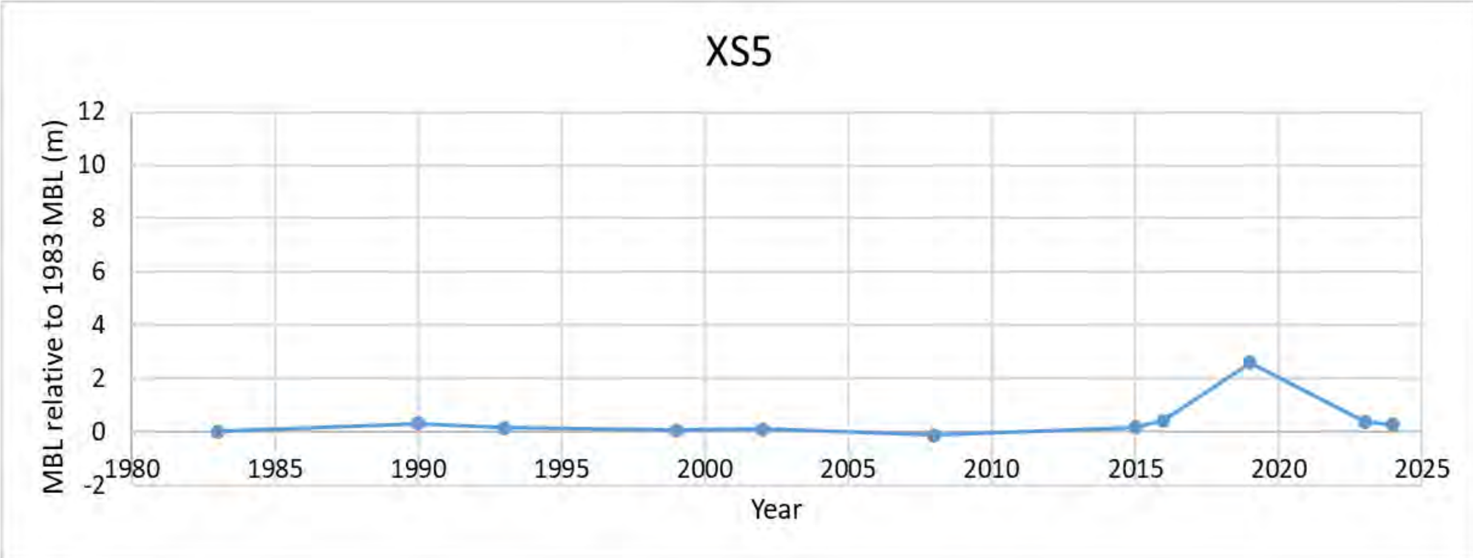
XS1
MBL relative to 1993 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year

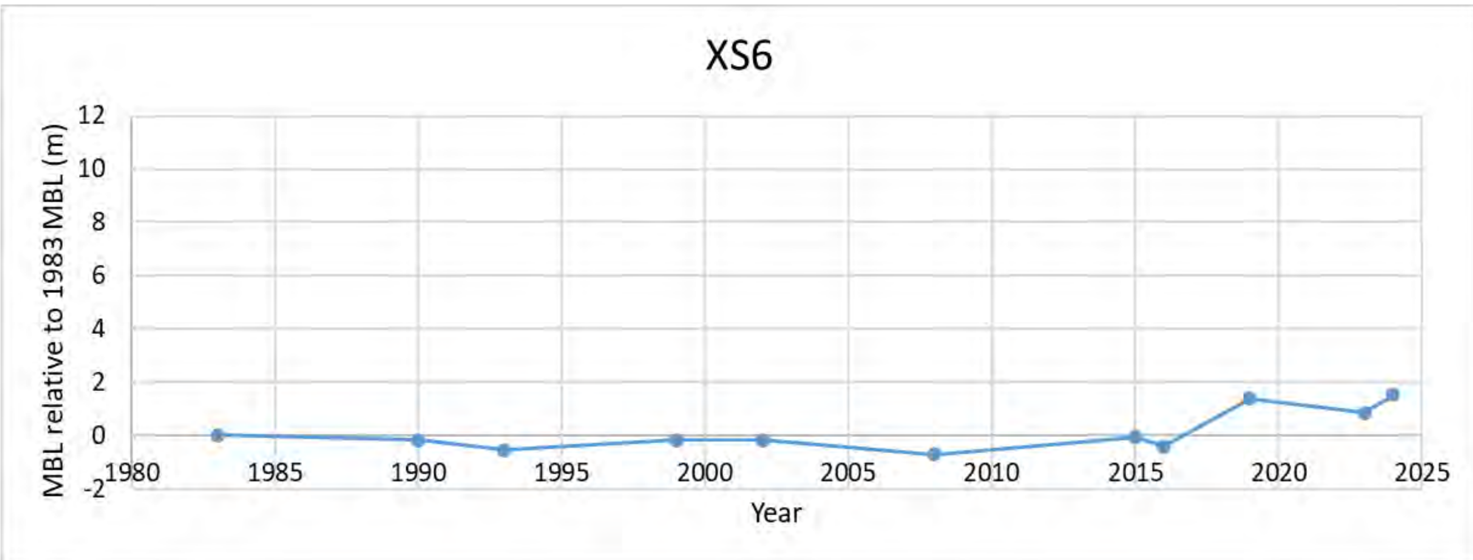

XS2
MBL relative to 1983 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year


XS3
MBL relative to 1983 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year

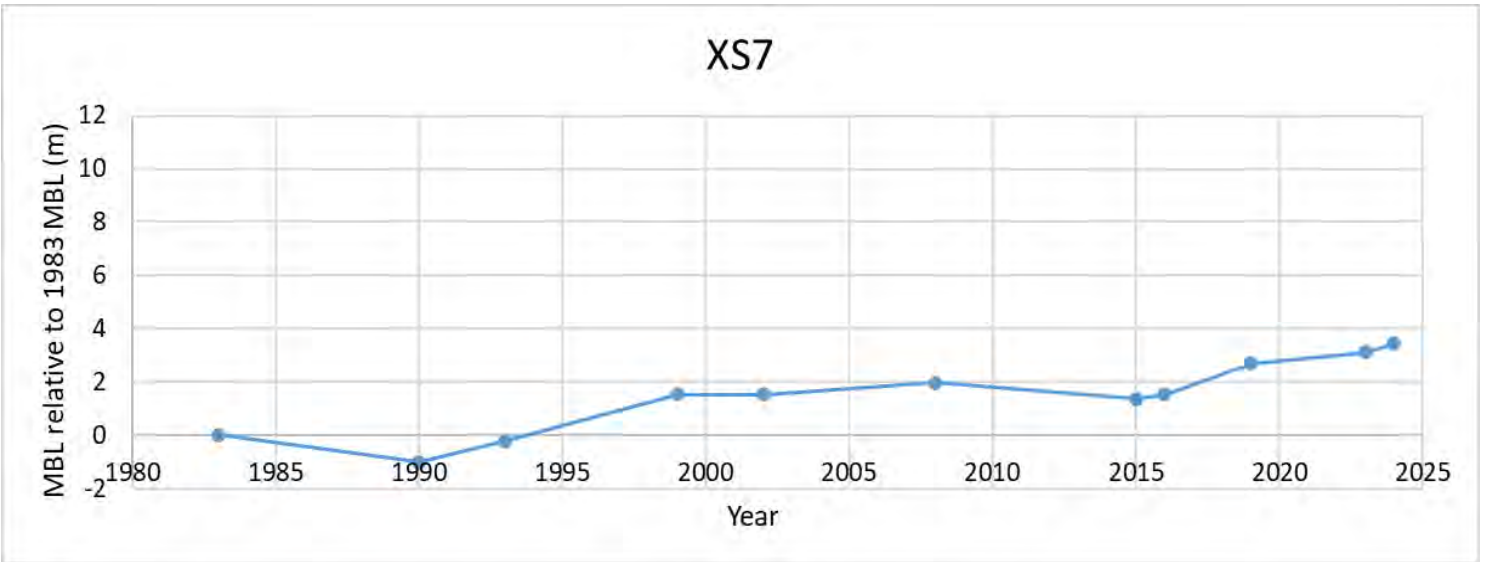

XS8
XS7
XS6
XS5
XS4
XS3
XS2
XS1

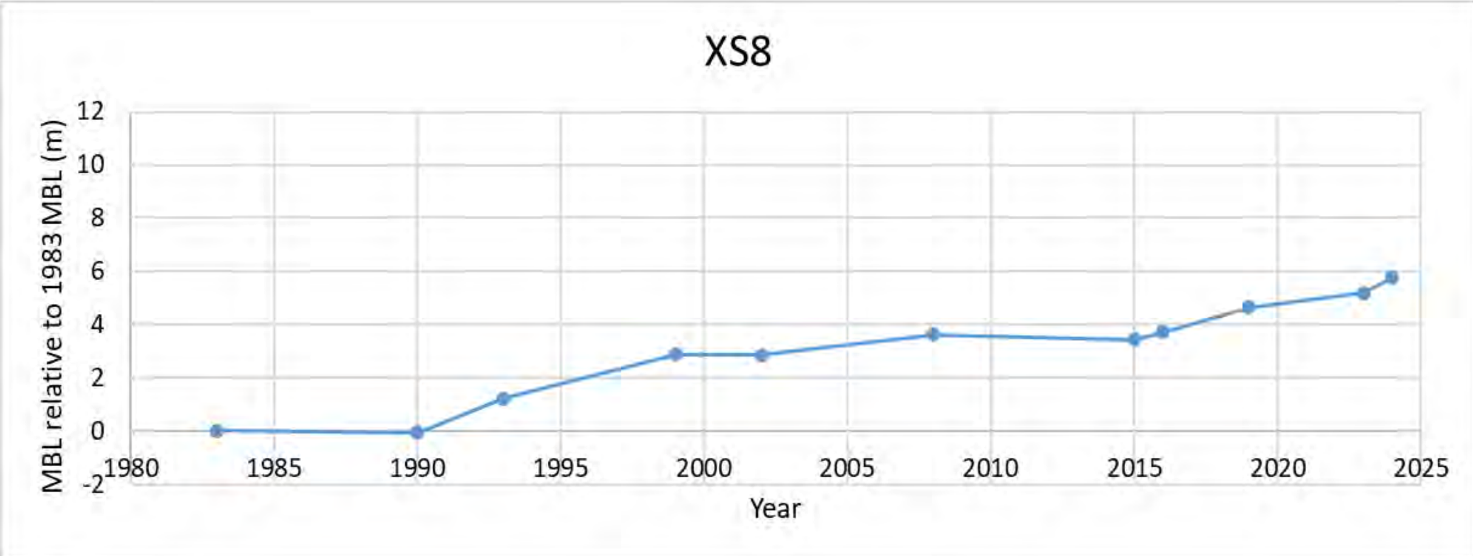

XS4
MBL relative to 1983 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year

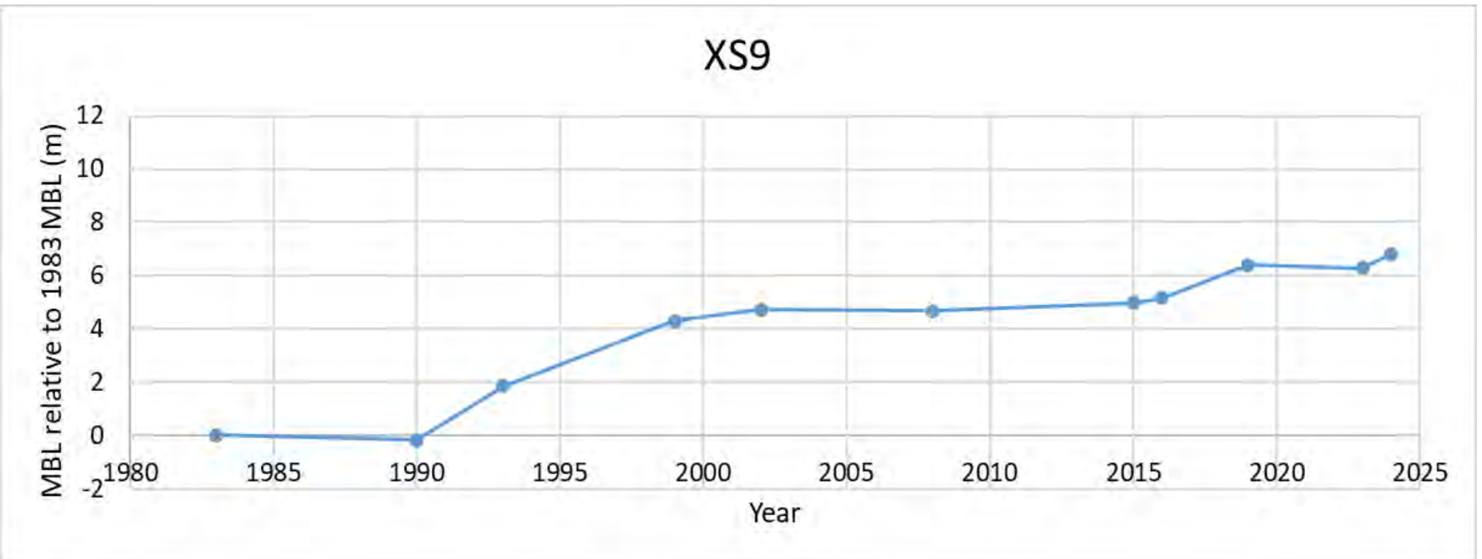

XS5
MBL relative to 1983 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year


XS6
MBL relative to 1983 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year

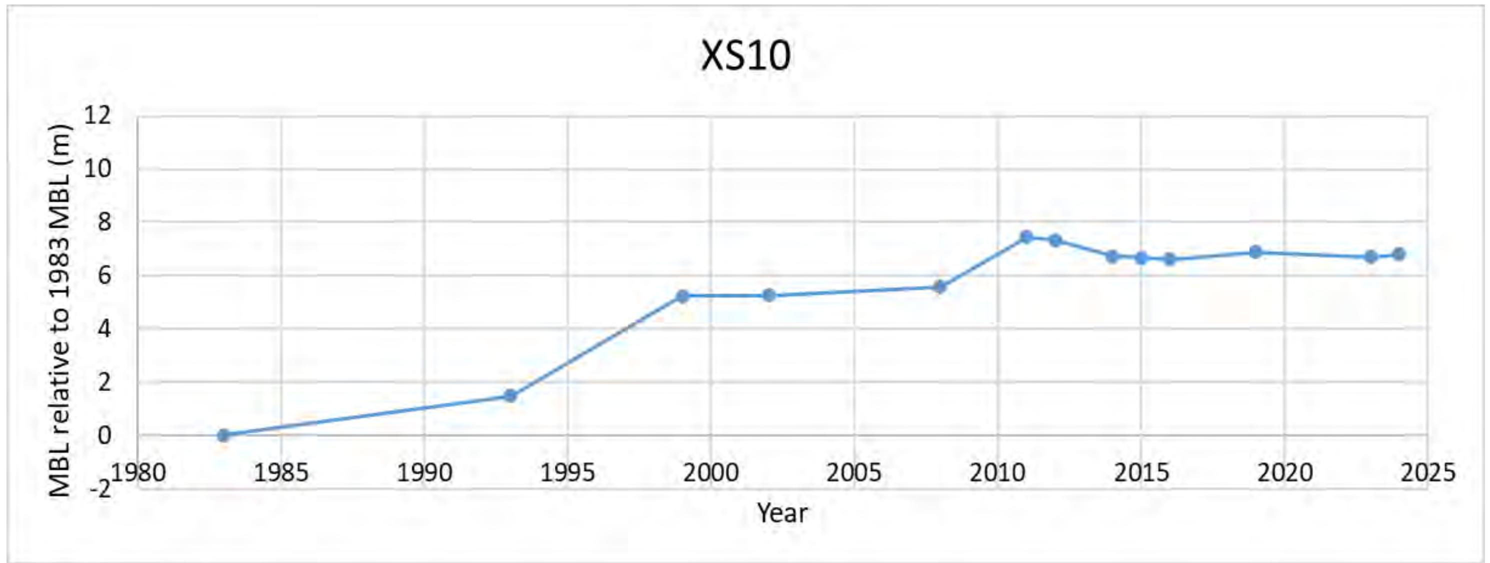

XS8
XS7
XS6
XS5
XS4
XS3
XS2
XS1

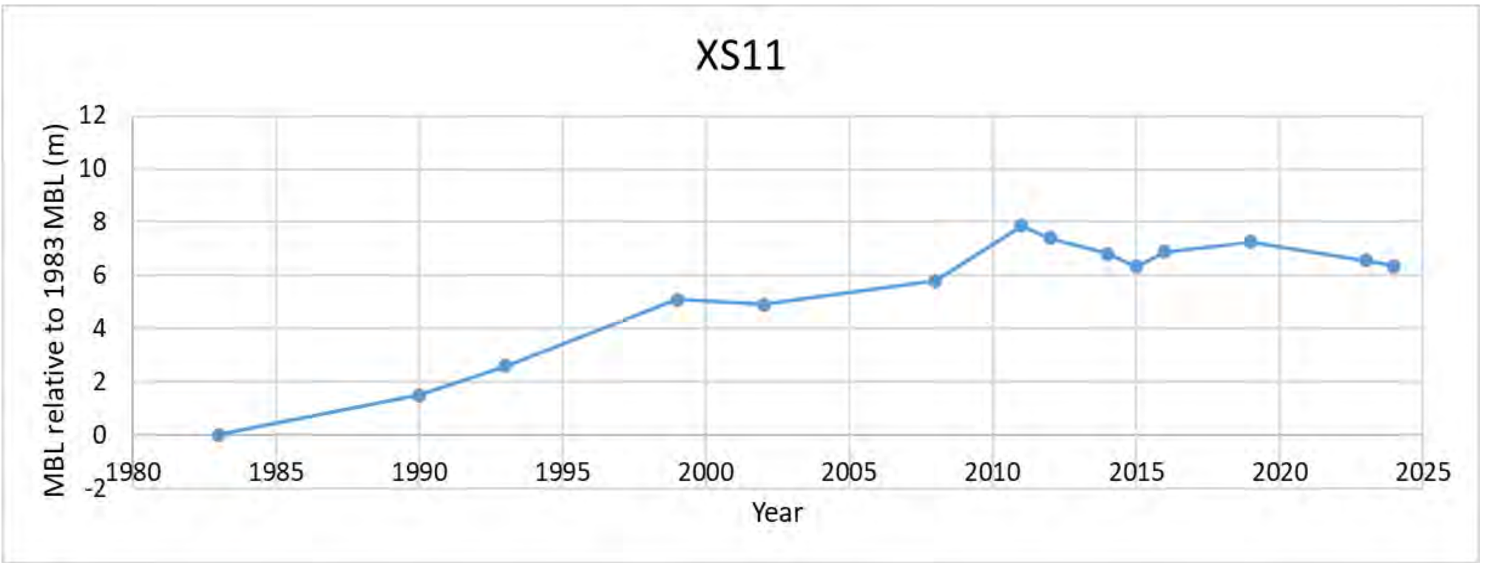

XS7
MBL relative to 1983 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year


XS8
MBL relative to 1983 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year


XS9
MBL relative to 1983 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year

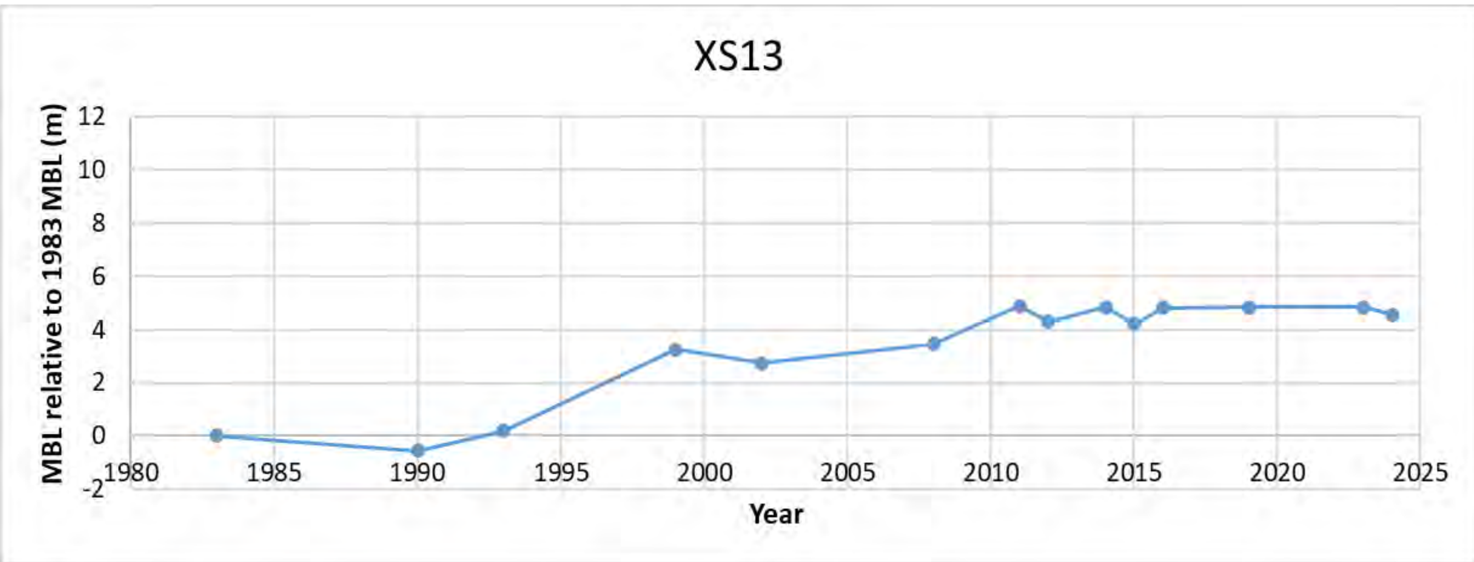

XS10
XS9
XS8
XS7
XS6
XS5
XS4
XS3
XS2

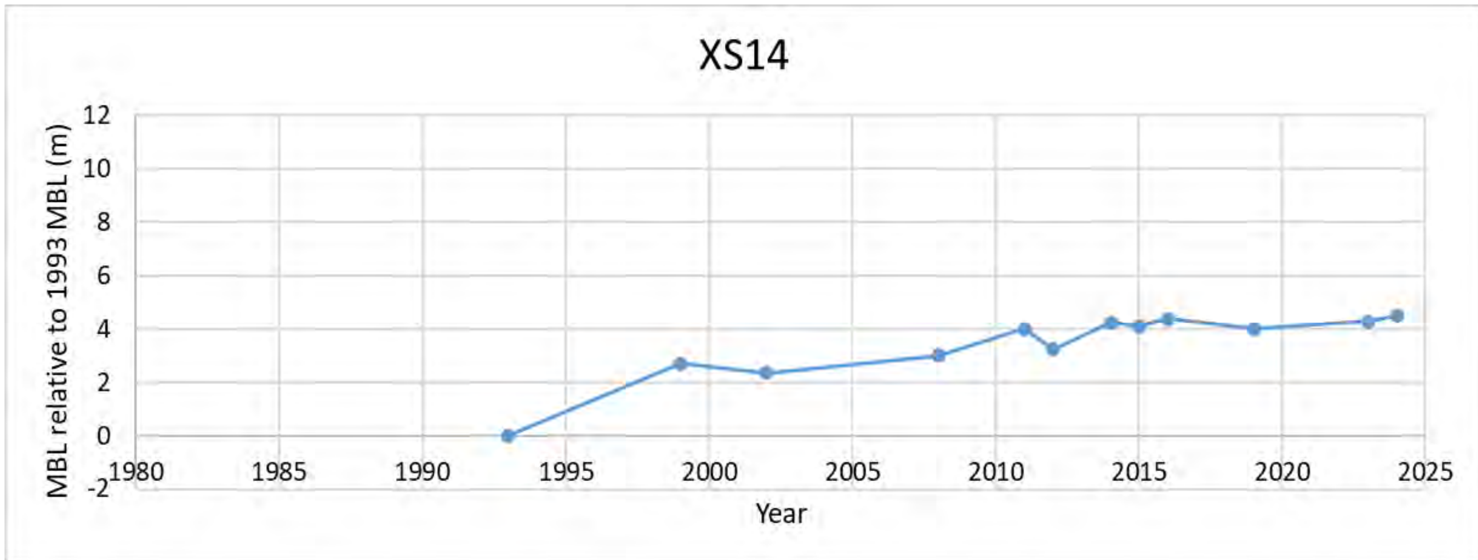

XS10
MBL relative to 1983 MBL (m)
Year

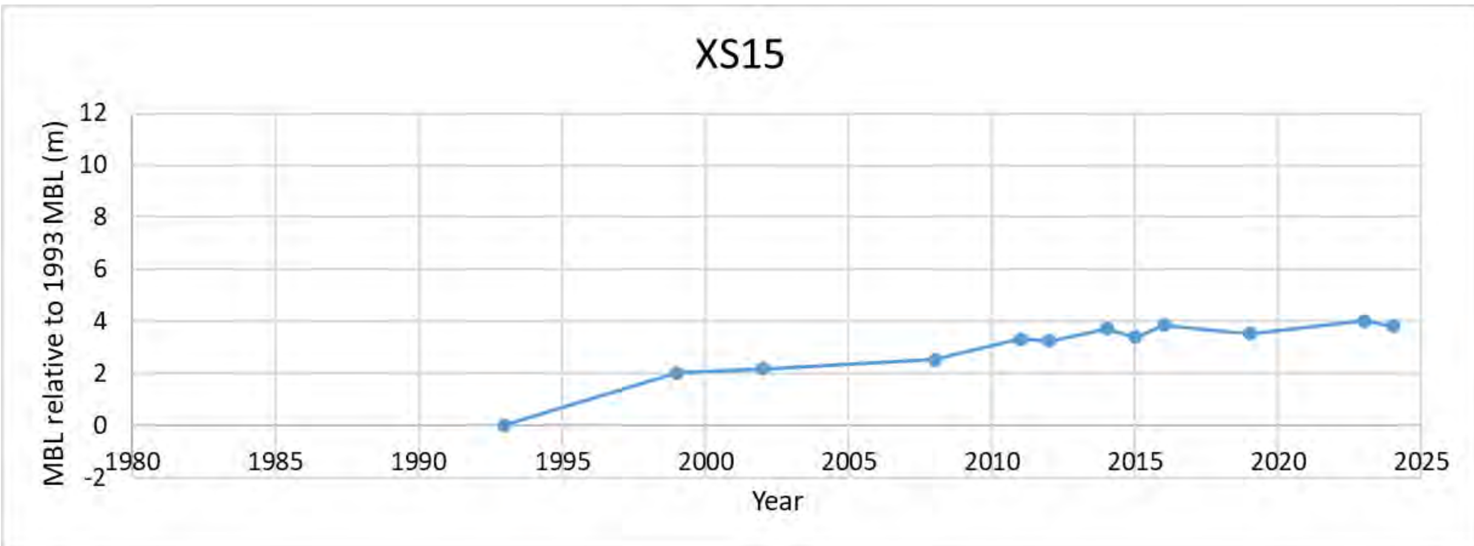

XS11
MBL relative to 1983 MBL (m)
Year


XS12
MBL relative to 1993 MBL (m)
Year

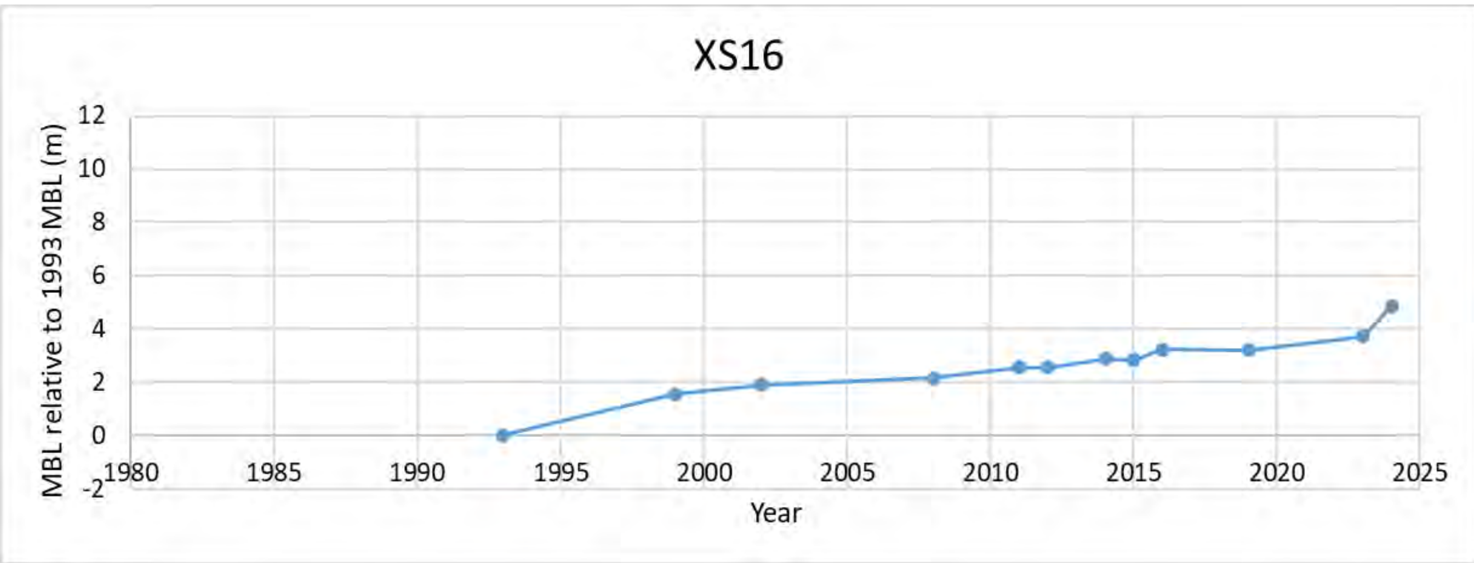

XS23
XS22
XS21
XS20
XS19
XS18
XS17
XS16
XS15
XS14
XS13
XS12
XS11
XS10

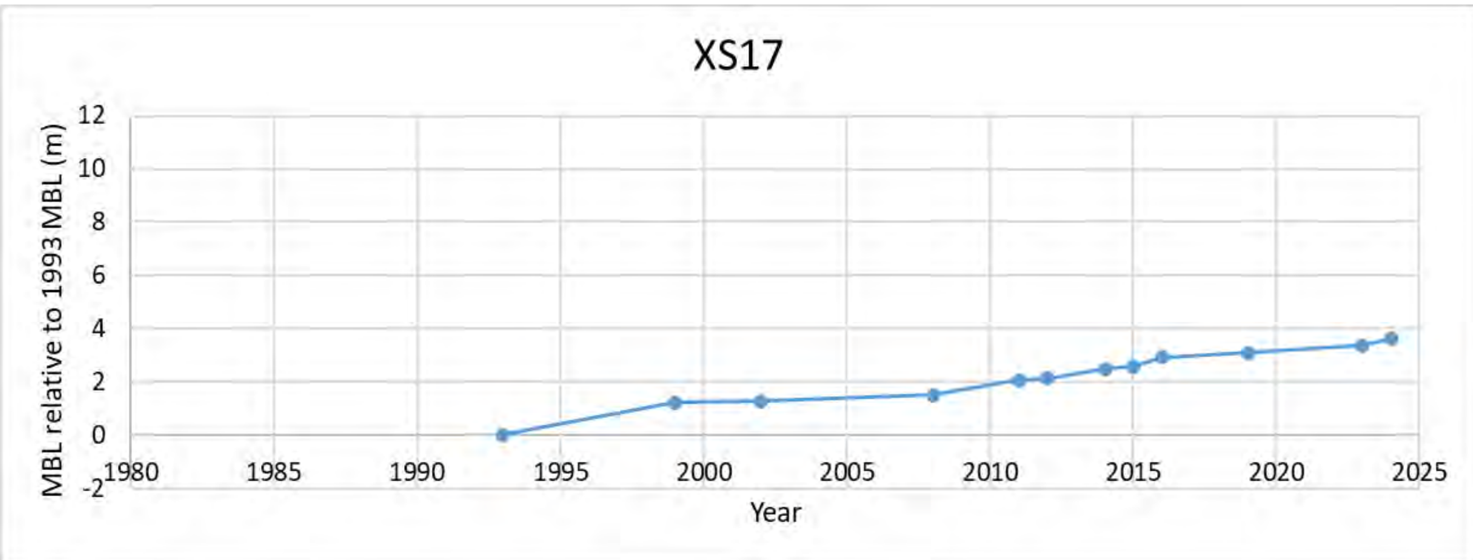

XS13
MBL relative to 1983 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year

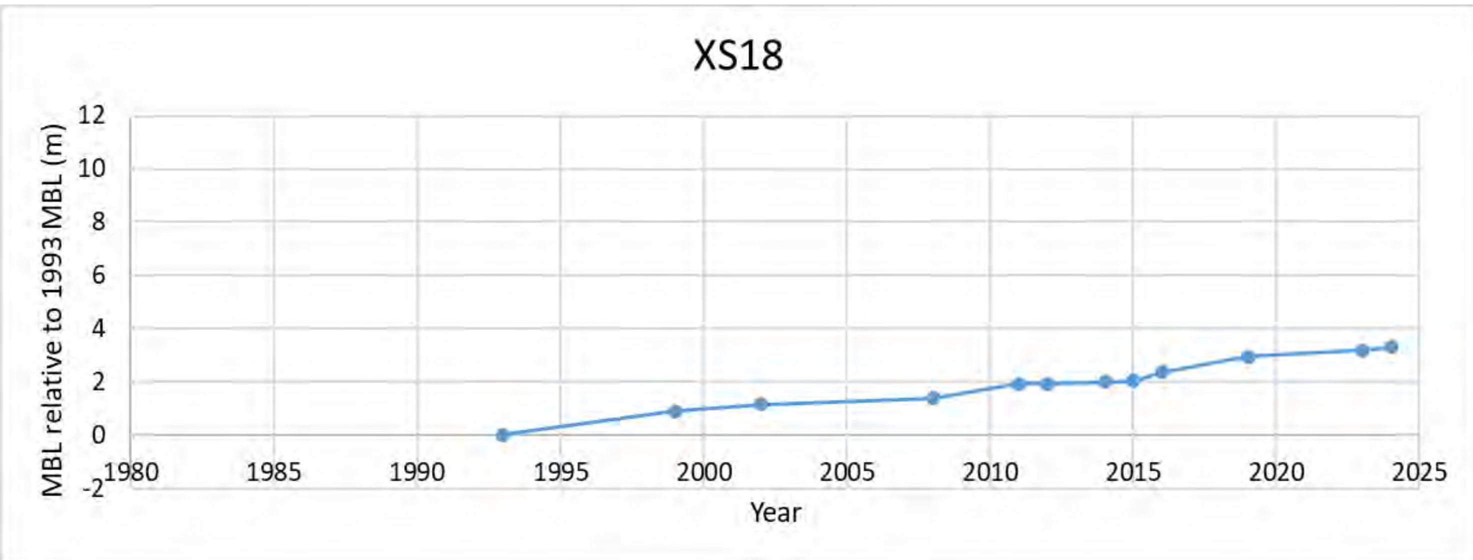

XS14
MBL relative to 1993 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year


XS15
MBL relative to 1993 MBL (m)
12
10
8
6
4
2
0
-2
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year

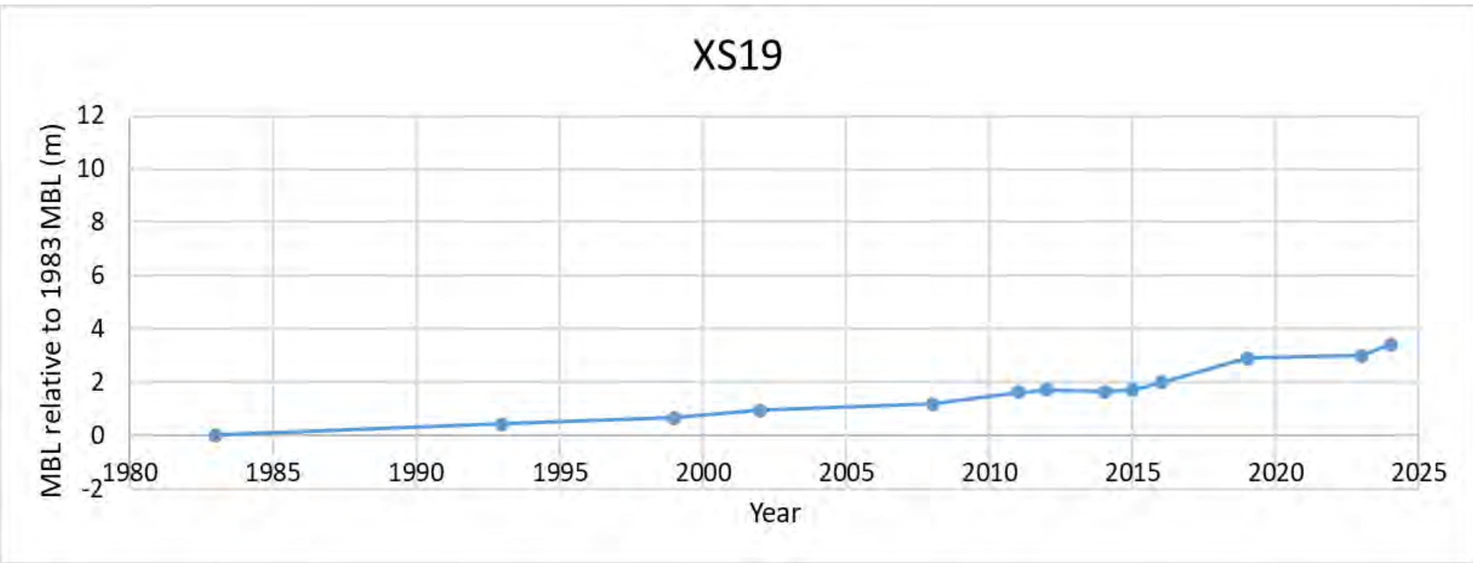

XS23
XS22
XS21
XS20
XS19
XS18
XS17
XS16
XS15
XS14
XS13
XS12
XS11
XS10

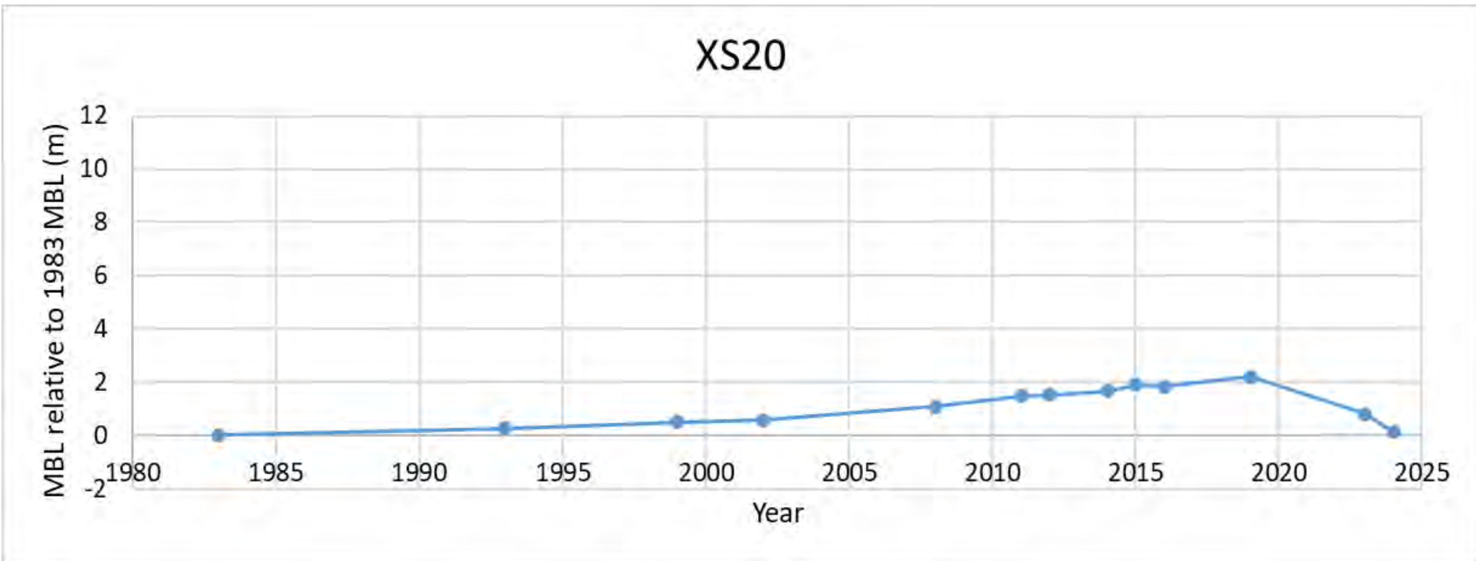

XS16
MBL relative to 1993 MBL (m)
Year

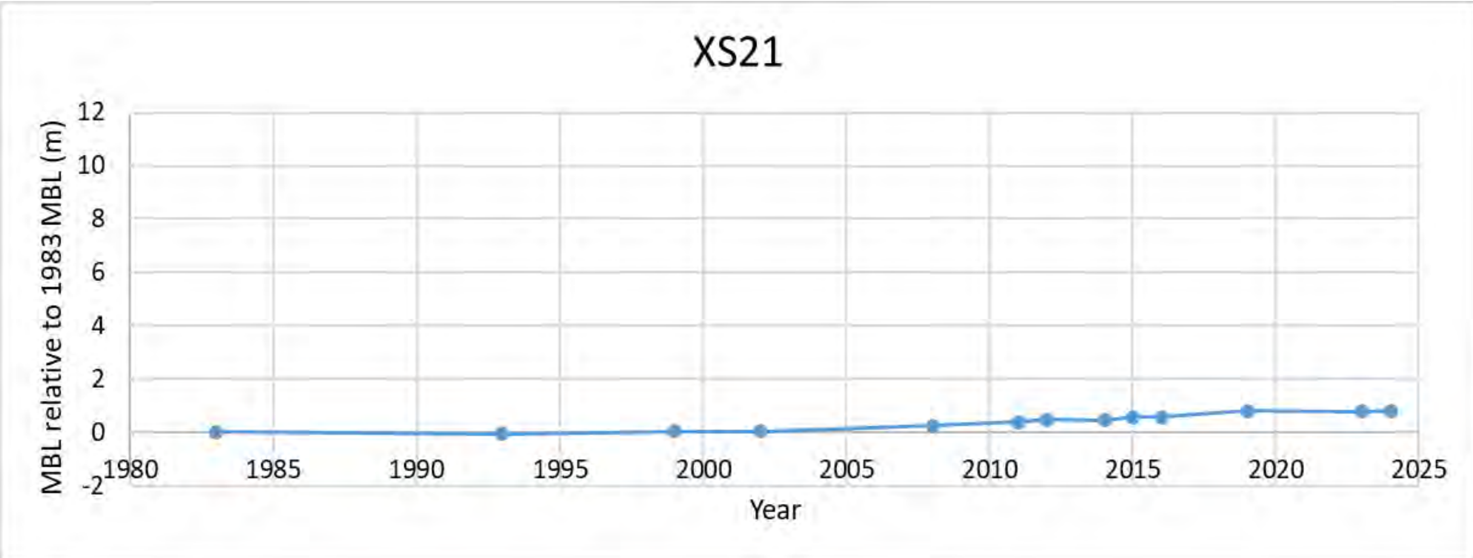

XS17
MBL relative to 1993 MBL (m)
Year


XS18
MBL relative to 1993 MBL (m)
Year

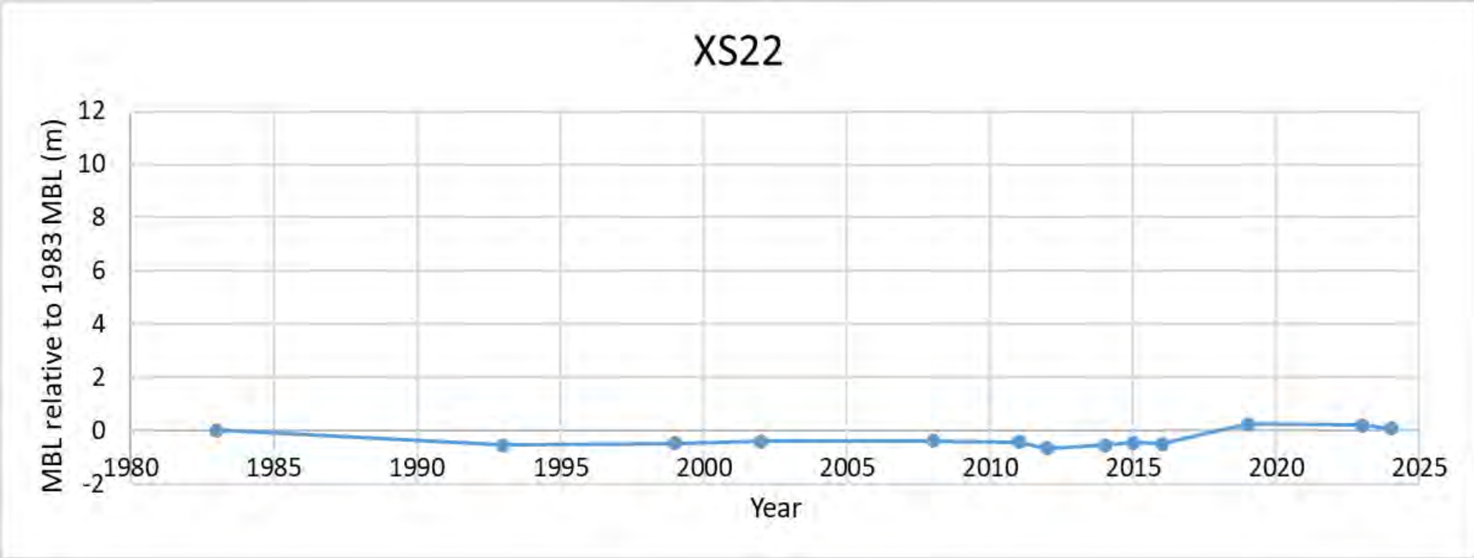

XS23
XS22
XS21
XS20
XS19
XS18
XS17
XS16
XS15
XS14
XS13
XS12
XS11
XS10

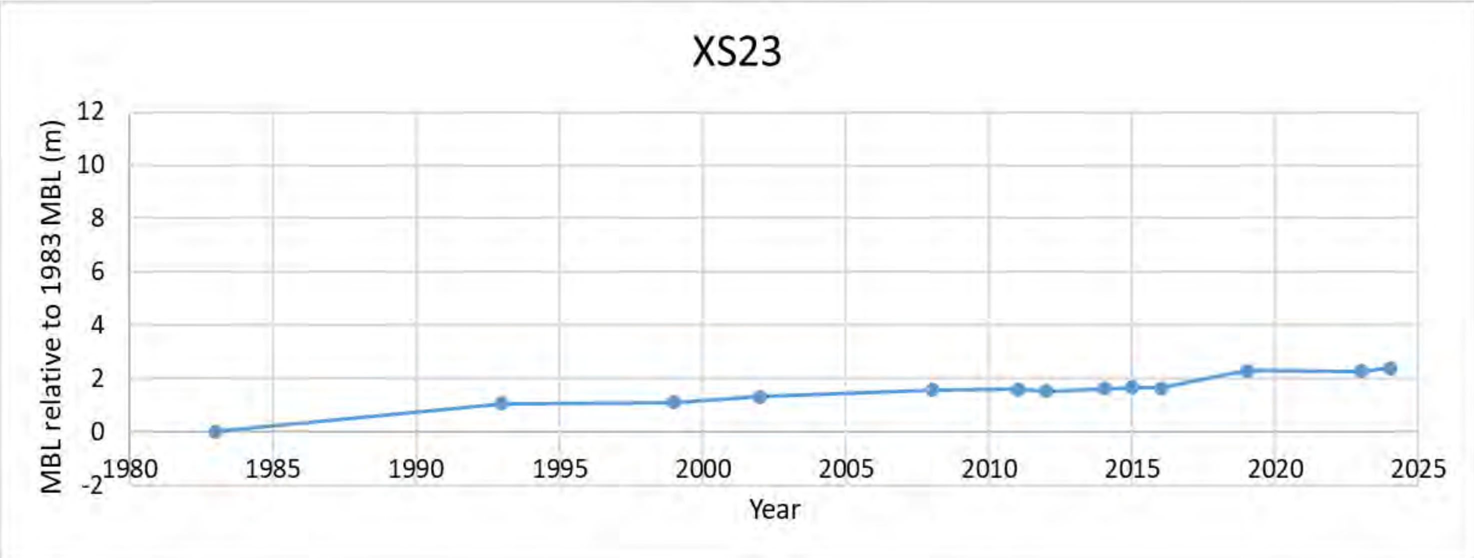

XS19
MBL relative to 1983 MBL (m)
Year


XS20
MBL relative to 1983 MBL (m)
Year


XS21
MBL relative to 1983 MBL (m)
Year


XS23
XS22
XS21
XS20
XS19
XS18
XS17
XS16
XS15
XS14
XS13
XS12
XS11
XS10





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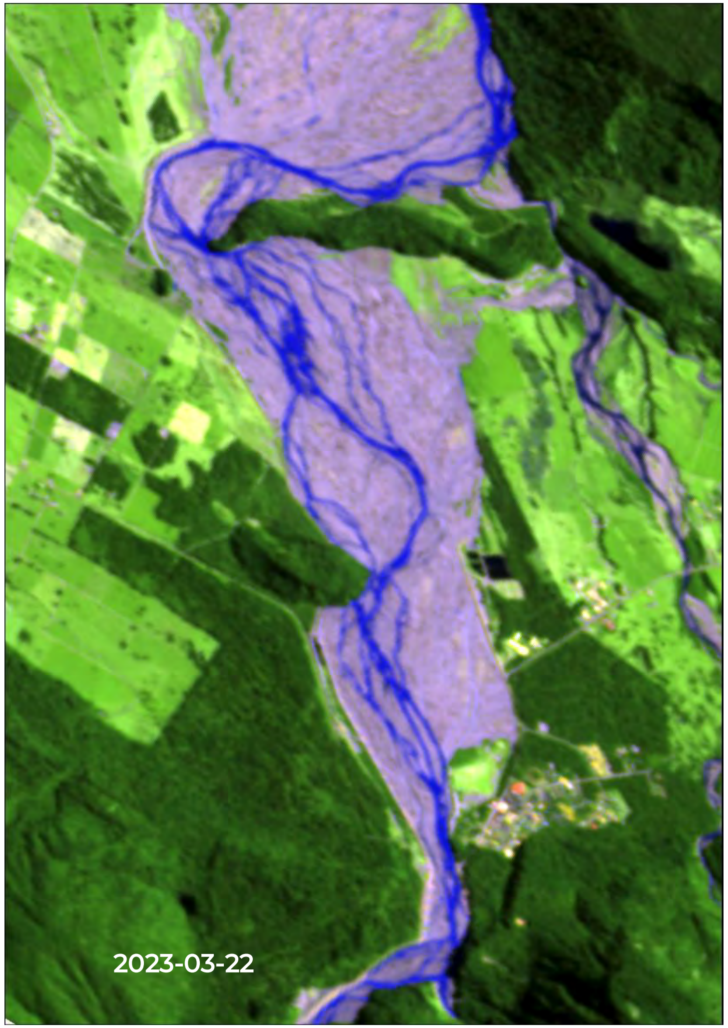
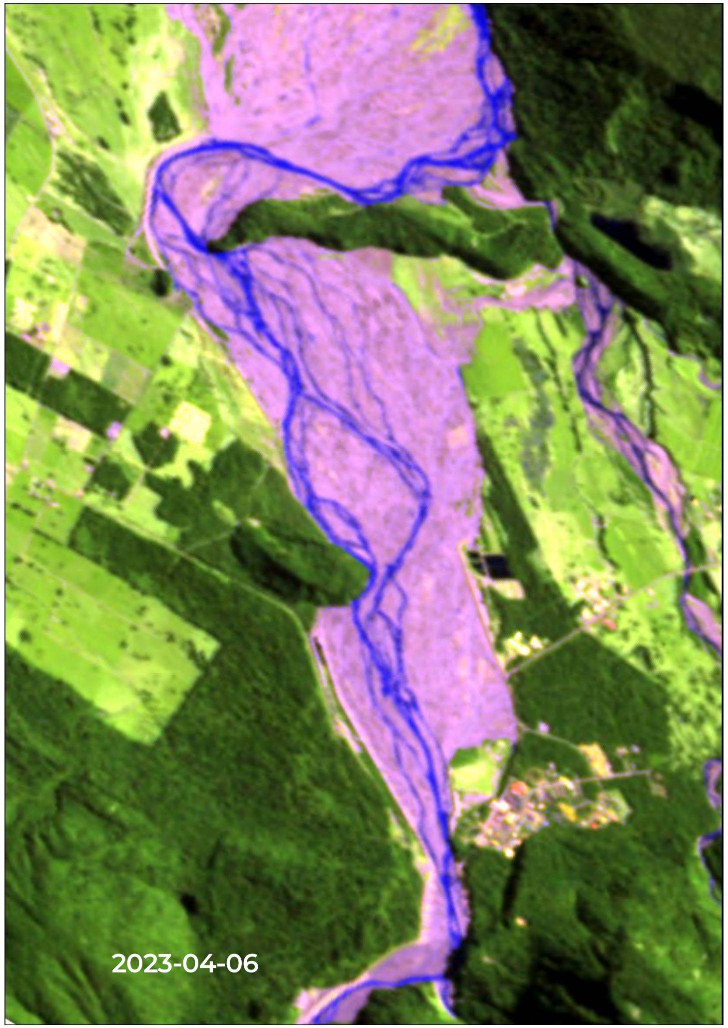
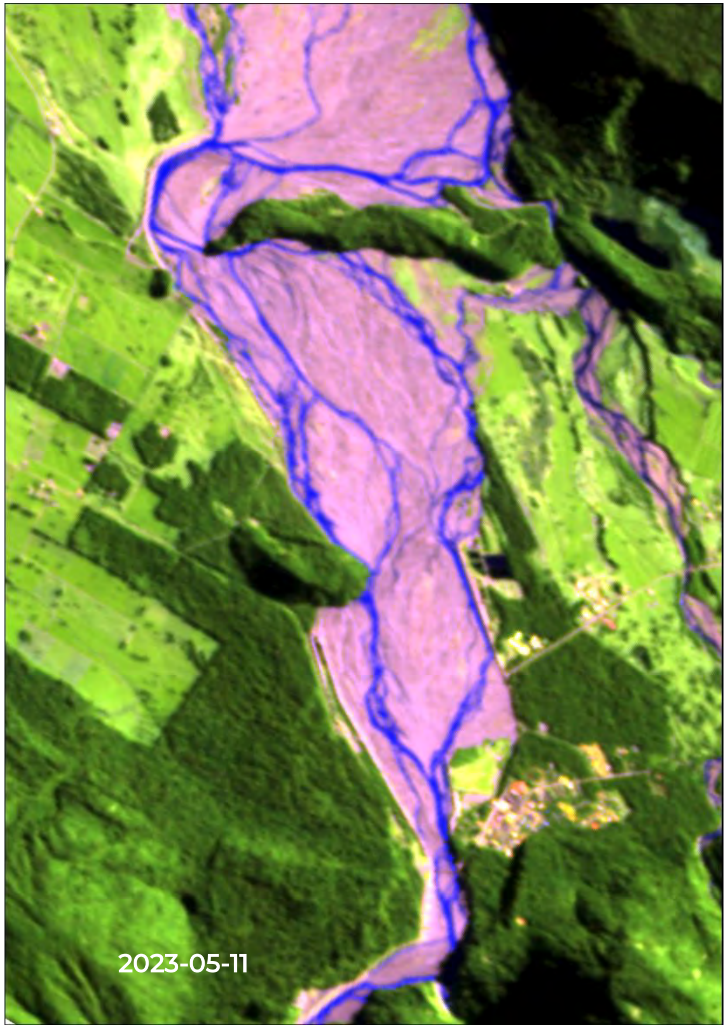
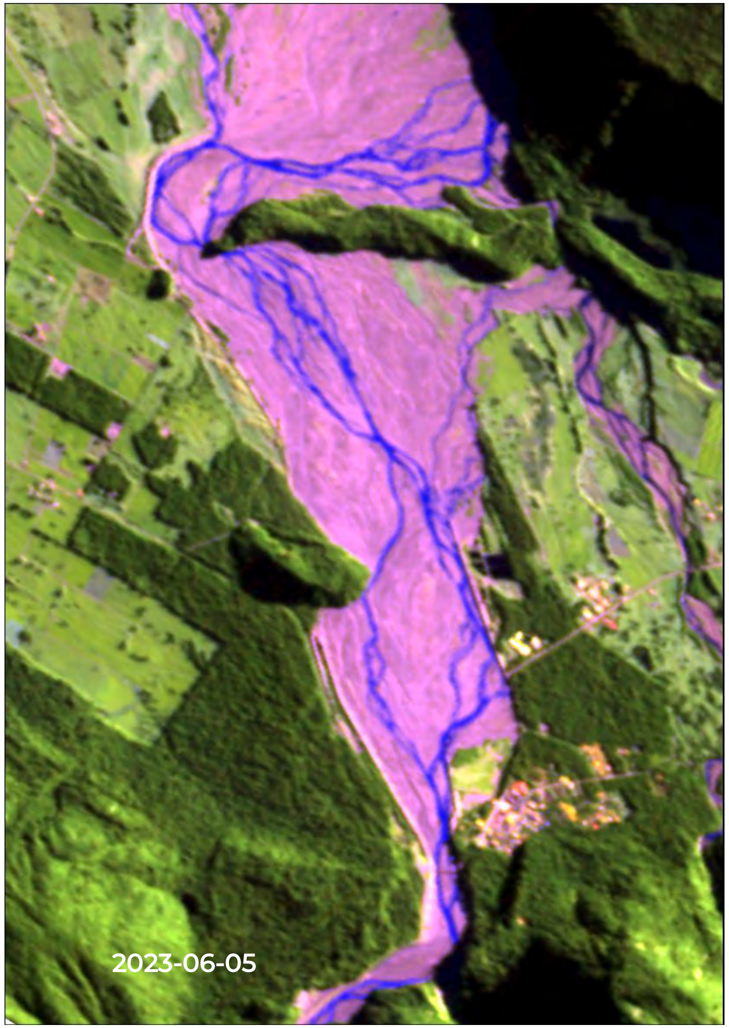
2023-02-10

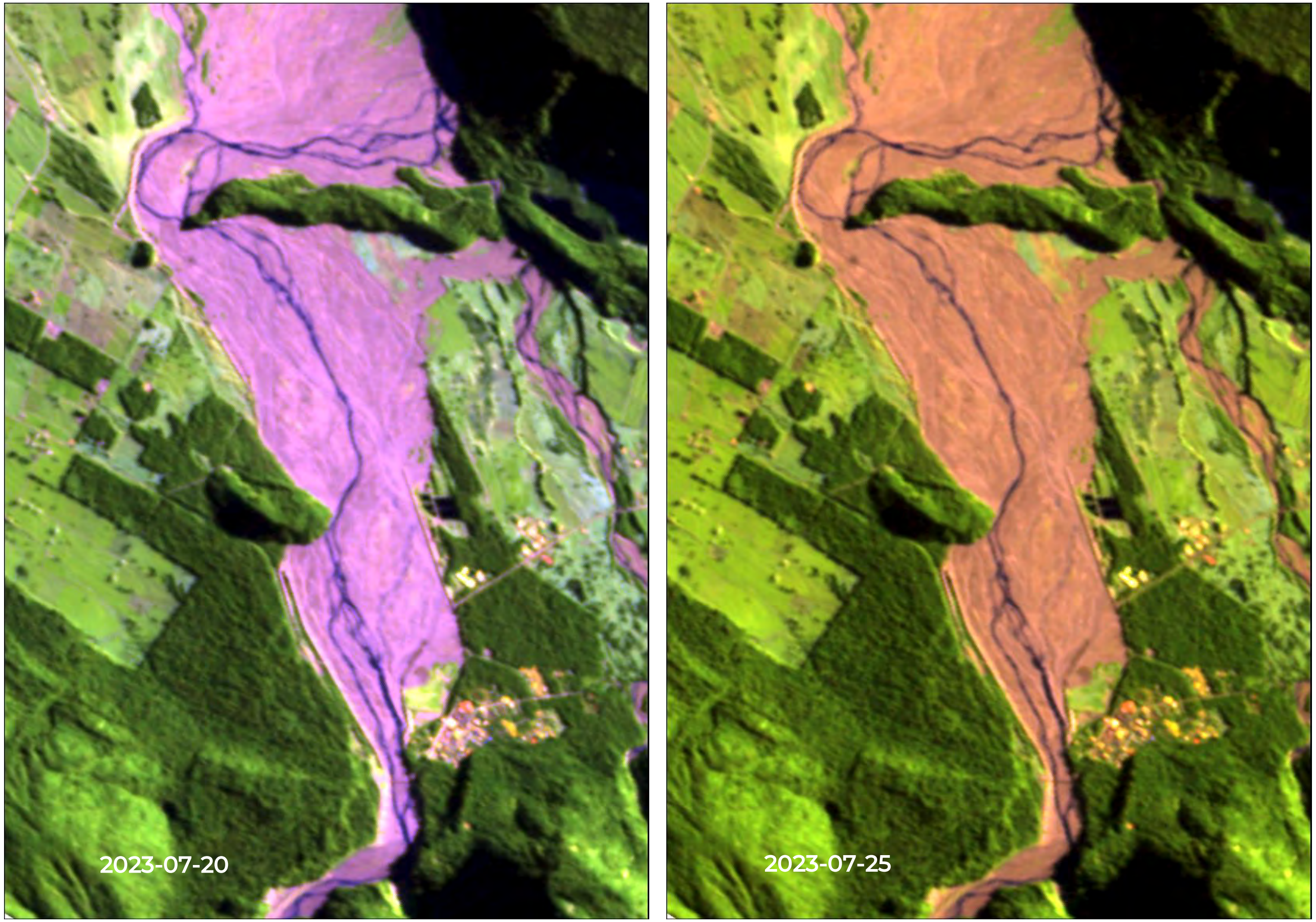

2023-02-25

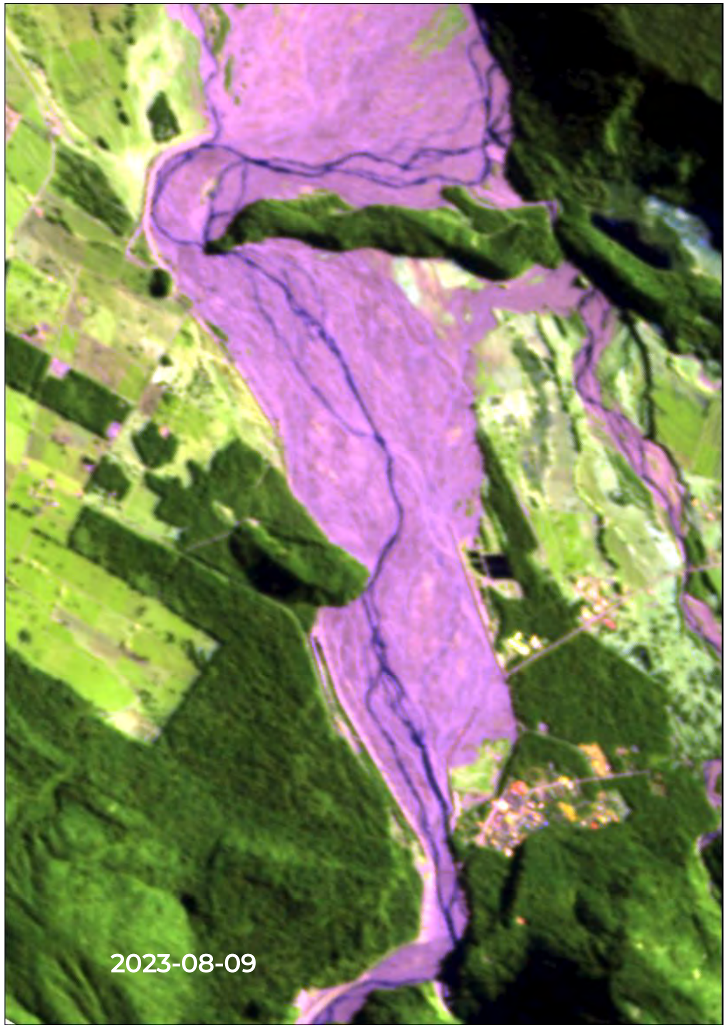

2023-03-22


2023-04-06


2023-05-11


2023-06-05


2023-07-20
2023-07-25



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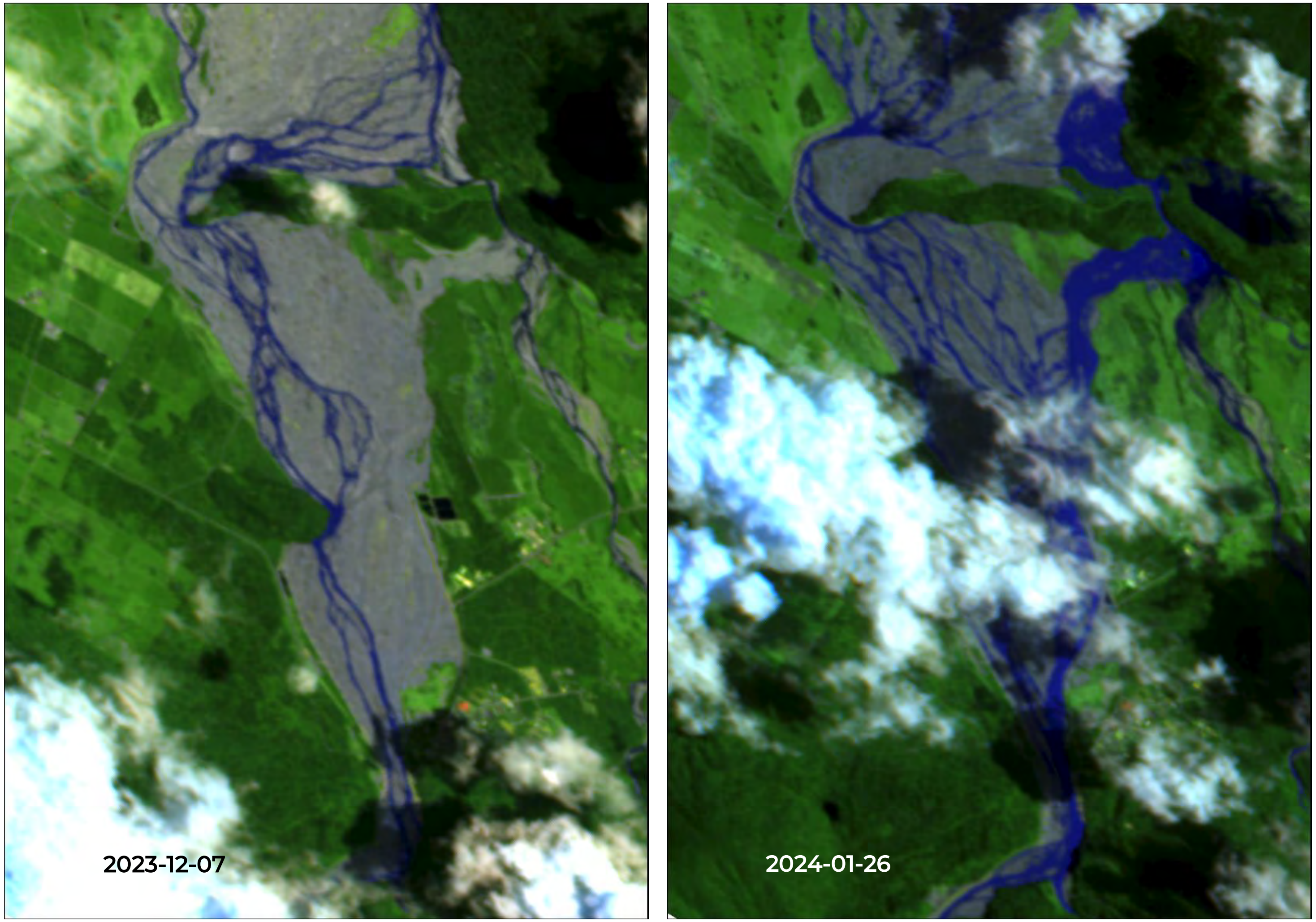

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Daily rainfall totals (mm) at the SH6 and Douglas Hut monitoring sites. The shading differentiates between the events in period of rainfall. The totals include all of the daily totals shown in each column.

February event 2023				January event 2024			
Month	**Day**	**SH6**	**Douglas**	**Month**	**Day**	**SH6**	**Douglas**
January	30th	38.5	45.5	January	18th	88.0	121
	31st	3.0	7.0		19th	211.0	255
February	1st	27.5	28		20th	10.0	13
	2nd	143.0	194.5		21st	5.5	5.5
	3rd	90.0	125		22nd	99.0	138
	4th	7.2	7.5		23rd	49.0	55.5
	5th	164.8	210				
	6th	21.5	28.5				
	7th	11.5	10				
	TOTAL	507.0	656.0		TOTAL	462.5	588.0

Monthly rainfall totals (mm; rounded to nearest whole number) recorded at both sites, and compared to the long term (LT) mean for each site. Monthly totals shaded blue exceed the LT mean, and shaded orange do not.

	2023											2024
	F	M	A	M	J	J	A	S	O	N	D	J
SH6 - 2023/24	542	595	518	817	173	177	194	555	502	262	543	732
SH6 - LT mean	421	362	390	464	380	400	381	429	474	439	524	516
Douglas - 2023/24	706	718	614	1054	273	211	267	756	738	405	627	884
Douglas - LT mean	411	424	418	479	471	383	411	556	607	539	643	574