# Clutha River morphology trends at Balclutha

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*Cover photo: Sentinel-2 satellite imagery of the Clutha River captured on 27th January 2025 showing the position of gravel bars.*

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# Executive summary

To help maintain the integrity of flood protection and gravel resources, the Otago Regional Council undertakes periodic cross-section surveys of the Clutha River. This report analyses eleven of these sections alongside Balclutha and explores how the morphology of the river has changed over the surveyed period from 1865 to 2024. Bed level rise or fall, in a given reach, depends on the supply of alluvial sediment from upstream and any changes in reaches immediately downstream. Overall, the cross-section data suggest a long-term trend of lowering of the river bed from the 1950s to about 2002 with less trend evident since 2002. This could correspond to the river adjusting to a reduction in bed load coming from upstream following commissioning of the Roxburgh Dam in 1954. Other influences which can affect sediment supply from upstream are flood size and frequency, bank erosion and protection measures, upstream catchment changes and gravel and gold mining activities. Mean bed level analyses showed that ten of the eleven cross sections are stable or degrading. Section C4 (at the State Highway Bridge) shows a weak rising trend in mean bed level. Minimum bed levels are stable or falling at all cross sections except C6 (North end of Elizabeth Street) where the surveyed low point is rising with time. This change may result from historic, upstream river training works.

Channel flood capacity depends not only on a cross section but is influenced by hydraulic roughness and downstream flow conditions. These effects are captured by flood gauging measurements. Analysing the gaugings at Balclutha since 1952, shows channel capacity is increasing for floods up to around 1600 $m^3/s$. The extent of flood scour is unknown at Balclutha but, assuming this has not reduced due to coarsening of the sediment size, the historic cross section surveys do not indicate reduction of flood capacity of the Balclutha reach.

There are several factors which could affect the findings of this report, namely: (a) River beds can temporarily scour during a rising flood and refill as a flood falls so that the true cross section at a flood peak may not be captured by a subsequent cross-section survey. A few Balclutha cross section surveys have been made during floods, but an earlier Clutha model study noted that significant scour, below the surveyed bed level, was required to pass historic flood flows at the observed flood levels; (b) There are recent reports that gravel bars are now more evident at Balclutha. It is assumed this is because a stable bar will become more visible and appear to be higher if the river level falls alongside the bar. A field inspection may shed light on this possibility; and (c) The effect of river bed gravel mining on cross sections is captured by the surveys but its effect is not quantified.

Ongoing monitoring and, in particular, measurement of bed levels during future high flood flows, is strongly recommended. This would quantify the degree of bed scouring induced by floods and help refine future hydraulic modelling.

# 1 Introduction

## 1.1 Background

The Otago Regional Council (ORC) have commissioned NIWA to analyse and report on historical changes in riverbed levels in the Clutha River/Mata-Au near the Balclutha township, using data from cross section surveys, flow gaugings and imagery. The cross section surveys were undertaken by ORC and pre-cursor organisations. The results of the analyses will be used to help understand the complex dynamic fluvial processes and to guide river management strategies into the future.

Data from eleven cross section locations have been used for this analysis. Seven of these cross sections are within the Clutha River, four are located on the branches where the river splits in two just downstream of Balclutha. Cross section surveys for ten of the locations have been undertaken regularly since 1994 and, for the cross section located near the railway bridge, data extend as far back as 1878. Data earlier than 2008 are the same as given in Otago Regional Council report: Channel morphology and sedimentation in the Lower Clutha River (2008). All cross sections are viewed and discussed from a "looking downstream" point of view.

In 1954, closure of the Roxborough Hydro dam cut part of the supply of coarser alluvial sediment to downstream reaches. Prior to this about 328 kt/yr of bed sediment would have arrived at Balclutha but only 24.5 kt/yr of bed material now arrives (Hicks et al. 2000). Other influences which could affect sediment supply from upstream are flood size and frequency, bank erosion and protection measures, upstream catchment changes and gravel and gold mining activities. The usual geomorphic response to a large decrease in sediment supply is downcutting (degradation) of the river channel. The degradation typically decreases with distance downstream from the dam and the rate of degradation generally reduces with time (Grant et al. 2003).

While the analysis covers a long period, morphological change can occur between the dates of cross section measurements, particularly if there is gravel extraction or flooding. Information on changes given herein relates purely to the net change between the survey dates. Any effect of gravel mining on cross section levels is not quantified.

An earlier Clutha model study (Smart and Bind 2006) noted that significant scour, below the surveyed bed level, was required to pass historic flood flows at the observed flood levels. Thus, the true river cross section during a flood peak, may not be captured by a subsequent cross section survey.

Channel capacity depends not only on the cross-sectional flow area but is influenced by hydraulic roughness and downstream conditions. These effects are captured by flood gauging measurements.

The vertical datum used throughout this report is Dunedin vertical datum 1958 + 100 m (added to avoid negative levels).

## 1.2 Scope of the work

The objectives of the study are to:

- Determine whether there is a significant trend in riverbed levels at Balclutha in recent decades, beyond the expected range of typical bed level fluctuations or measurement uncertainties.

- Assess notable changes in the location, scale, or development of gravel bars or islands within this reach of the river.
- Identify the key factors driving any significant changes observed or, in the absence of such changes, to explore the reasons behind community perceptions of change in the river system.
- Evaluate whether the magnitude of any observed riverbed level changes is sufficient to reduce the flood capacity within this reach of the river.

To address these objectives, we have undertaken the following steps in our analysis:

- Collating all available ORC surveys and riverbed cross section data.
- Reviewing the raw survey data and refining it where discrepancies or mismatches with historical cross-section records were identified, ensuring consistency and accuracy.
- Overlaying and plotting the cross sections to provide a clear visual representation of changes over time.
- Analysing historical changes in riverbed levels by calculating the mean bed level and the minimum bed level for each cross section location.
- Evaluating changes in the extent of gravel bars by calculating the ratio of the area above the mean bed level to the cross section width, enabling an assessment of spatial trends in bar development.
- Using satellite imagery over time to analyse changes in the extent of gravel bars.
- Investigating the flow gauging record from the NIWA flow recorder site at Balclutha.

# 2 Cross section data and adjustments

Cross section surveys of the Clutha River, covering the Balclutha township area, are used to assess historical changes in bed level. These surveys are for cross section locations C1 to C7, K12, K13, M12 and M11. The location of these cross sections is shown in Figure 2-1. More information on the cross sections is provided in ORC (2008).

Although most cross sections were surveyed between 1994 and 2024, the specific years of surveys vary for the different cross section locations. Notably, for cross section C2, located at the present railway bridge, survey records extend further back, with the earliest data dating to 1878. Table 2-1 provides a summary of the number of surveys conducted at each cross section and the corresponding years of data collection. Cross section surveys conducted in 2023 were excluded from this study due to unexplained discrepancies when compared to both previous and subsequent surveys.

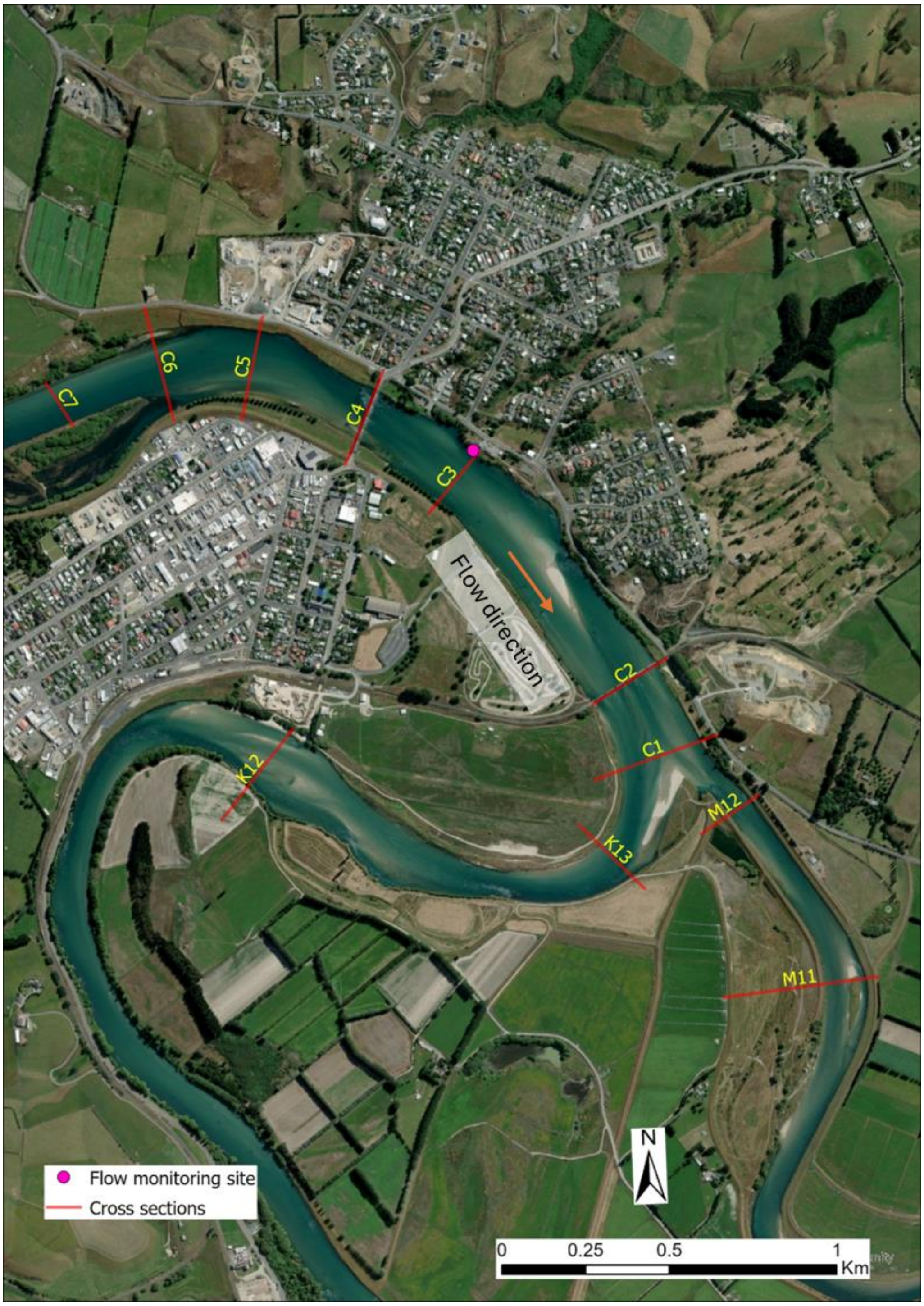



**Figure 2-1: The location of cross section surveys on the Clutha River at Balclutha together with the flow monitoring site.** The flow monitoring site is "Clutha at Balclutha".

**Table 2-1: Cross section data from the Clutha River near Balclutha township.** These data were used for the analysis historical bed level changes.

| Cross section | Description | Number of surveys | Years* |
|---|---|---|---|
| K13 | First downstream cross section of Koau branch | 7 | 1994, 2002, 2005, 2014, 2019, 2020, 2024 |
| K12 | Second downstream cross section of Koau branch | 7 | 1994, 2002, 2005, 2014, 2019, 2020, 2024 |
| M12 | First downstream cross section of Matau branch | 7 | 1994, 2002, 2005, 2014, 2019, 2020, 2024 |
| M11 | Second downstream cross section of Matau branch | 7 | 1994, 2002, 2005, 2014, 2019, 2020, 2024 |
| C1 | Most downstream cross section before Clutha River splits into Matau Branch and Koau Branch | 11 | 1994, 1995, 1996, 1997, 2001, 2002, 2005, 2014, 2019, 2020, 2024 |
| C2 | Cross section near railway bridge | 14 | 1878, 1893, 1939, 1994, 1995, 1996, 1997, 2001, 2002, 2005, 2014, 2019, 2020, 2024 |
| C3 | Cross section next to flow monitoring site | 9 | 1994, 1995, 1996, 2002, 2005, 2014, 2019, 2020, 2024 |
| C4 | Cross section near Highway 1 bridge | 8 | 1994, 1995, 1996, 1997, 2001, 2002, 2019, 2020, 2024 |
| C5 | Around 400m upstream of the Highway Bridge | 10 | 1994, 1995, 1996, 1997, 2002, 2005, 2014, 2019, 2020, 2024 |
| C6 | North end of Elizabeth Street, Balclutha | 10 | 1994, 1995, 1996, 1997, 2002, 2005, 2014, 2019, 2020, 2024 |
| C7 | Most upstream cross section analysed | 10 | 1994, 1995, 1996, 1997, 2002, 2005, 2014, 2019, 2020, 2024 |

* 2023 survey data are considered unreliable and are not listed here.

When analysing the cross section database, several inconsistencies were identified across different surveys for various cross sections. For example, there was consistent horizontal displacement across some cross sections while the shape of their high banks remained identical (Figure 2-2). In our comparison of bed level changes, corrections have been made to surveys having obvious offset errors. These corrections were identified by overlaying consecutive surveys and measuring the horizontal offsets. These offsets are listed in Appendix A (Table A-1).

To ensure comparability of cross-section analyses, consistent start and end points were selected for each cross-section. These points were selected to encompass measurements from all surveyed years, allowing for a reliable comparison of changes over time. For surveys conducted in years where selected end points lacked measured elevation data, elevations were estimated using linear interpolation between the closest measured points. In cases where the surveys did not fully cover the start and end points, extrapolation was used to estimate the missing elevations (Figure 2-2). Table 2-2 summarizes the end point offsets and riverbed width used in the analysis of cross section data.

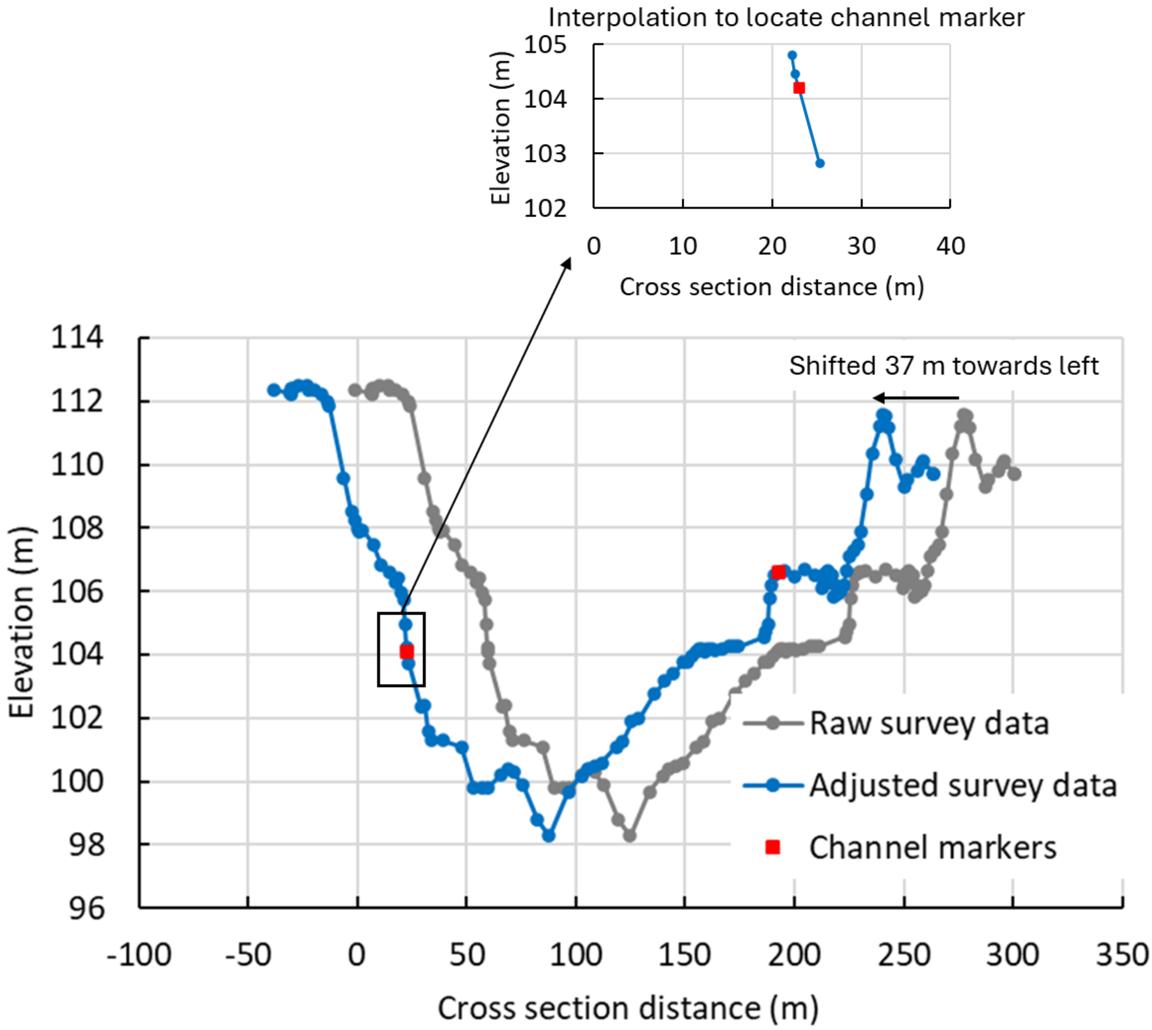



**Figure 2-2: Example of cross section data correction and interpolation between the measured points to find consistent start and end point for all surveyed years.** Data shown are for cross section C4 in 2020.

**Table 2-2: End-point offsets and riverbed widths used for cross section data analysis including mean bed level calculations and area above mean bed level.** Left and right bank offsets relate to the section survey data.

| Cross section | Left (m) | Right (m) | Width (m) |
|---|---|---|---|
| K12 | 7.2 | 205.0 | 197.8 |
| K13 | 3.7 | 125.8 | 122.1 |
| M11 | 4.5 | 129.0 | 124.5 |
| M12 | 5 | 85.7 | 80.7 |
| C1 | 2.2 | 260.0 | 257.8 |
| C2 | 26.0 | 255.0 | 229.0 |
| C3 | 9.0 | 186.0 | 177.0 |
| C4 | 23.0 | 193.0 | 170.0 |
| C5 | 6.0 | 204.0 | 198.0 |
| C6 | 4.0 | 249.0 | 245.0 |
| C7 | 8.0 | 159.0 | 151.0 |

Figure 2-3 shows the final C1 cross section plot for all surveyed years in a form which can be used for further analysis and calculation of parameters. The remainder of the similarly processed cross section plots are shown in Appendix B. Grey vertical lines indicate the start and end point that is used for analysis of bed level change.

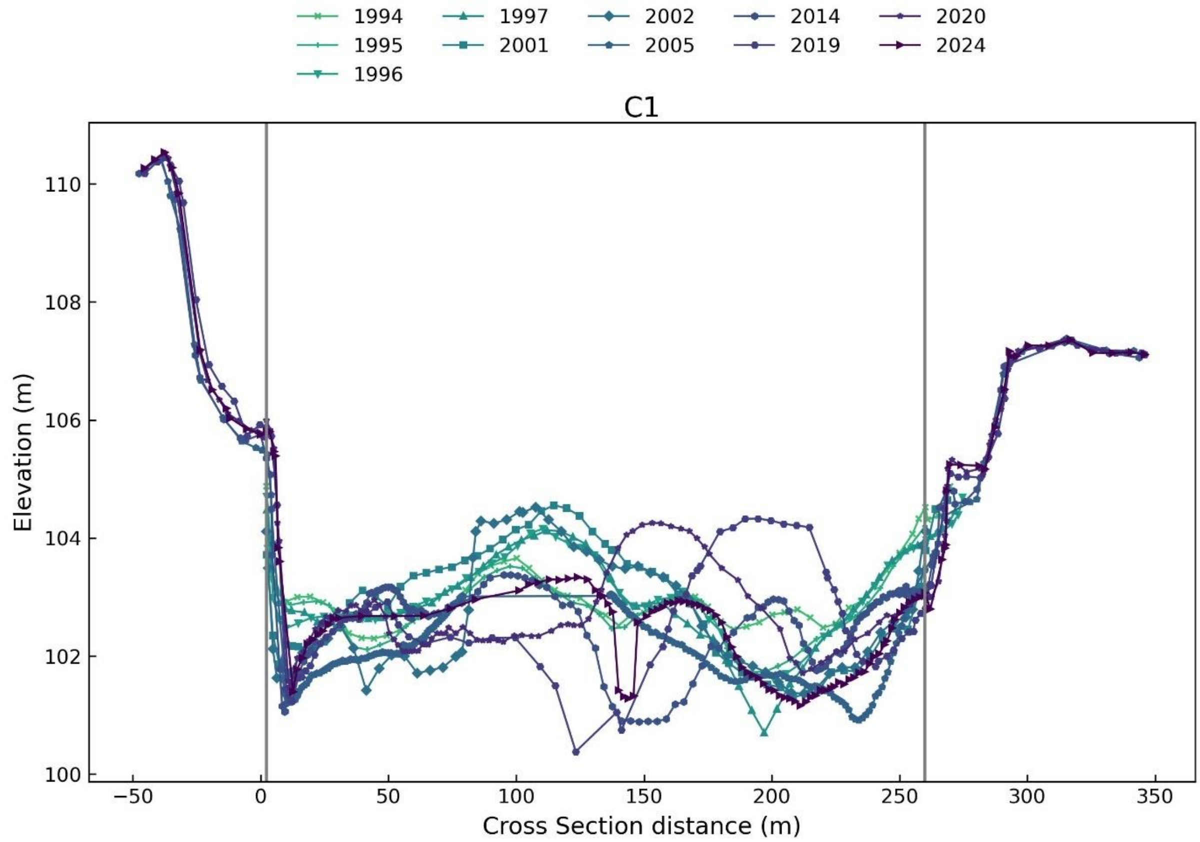



**Figure 2-3: C1 cross sectional profile for all surveyed years.** Grey vertical lines indicate the start and end points used for analysis of bed level change. The rest of the cross sections are plotted in Appendix B.

## 2.1 Cross section data analysis

To monitor changes in the riverbed and quantify any variations in the cross sections that have occurred over the years, a set of parameters is used:

- mean bed level.
- area above mean bed level divided by width.
- minimum bed level.
- stage for flow.

The mean bed level (MBL) was calculated between the same end points for each survey, summing the area above datum and dividing this area by the distance between the end points. Tracking changes in the MBL over time allows for the assessment of long-term river stability, helping to determine whether the riverbed is experiencing aggradation or degradation across different time intervals.

The minimum bed level (minBL) refers to the lowest point on the surveyed cross section. In some studies, minimum bed level is also referred to as the thalweg level. Comparing changes in the minimum bed level over time provides insights into sedimentation and erosion processes occurring in the deepest areas of the channel.

The cross section “area above mean bed level” was calculated by subtracting the cross section mean bed level from the elevation of each cross section point and determining the total area of the cross section lying above the mean bed level line.

Figure 2-4 shows the approach used to calculate this term for cross section C1 in 2024. The area above mean bed level was divided by the total width (as listed in Table 2-2) to give a consistent comparison between cross sections. The resulting average-height-above-mean-bed-level parameter helps quantify changes in morphological features across the river cross section. An increase in this parameter through time, means increased variation in bed levels across a cross section, which can indicate features such as sand or gravel bars or deeper channels forming.

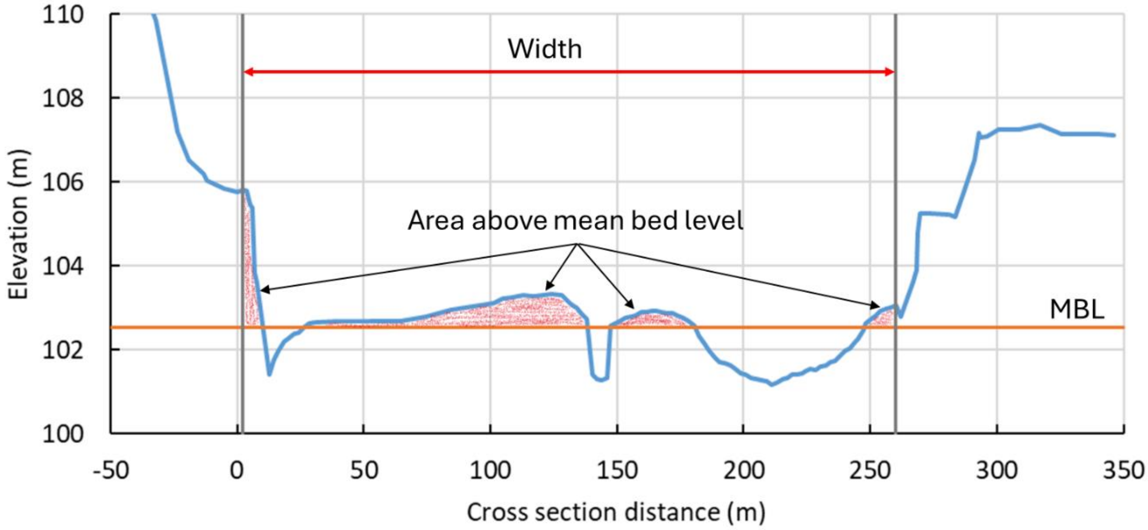



**Figure 2-4: Illustration of area above mean bed level for cross section C1 in 2024.**

The along-river distance of each cross section was measured accurately in GIS by digitising the centreline of the active channel as a smoothly curving line. These river distances were used to plot longitudinal river profiles. River distances were measured relative to cross-section C1 with positive distances representing upstream cross sections and negative distances downstream.

# 3 Satellite imagery

Sentinel-2 imagery was used to capture projected images and study river bars in the area of interest. As bars appear larger at lower flows and vice versa, comparison of bar sizes and positions at different times, should be made when there are similar flows in the river. Seven images from the period between 2016 and 2025 were selected on the basis of two criteria:

- Cloud cover of less than 10% to ensure a clear view of the river and gravel bars.
- Similar low-flow conditions, determined by selecting dates when there was satellite image acquisition and a low daily mean flow.

The selected imagery was downloaded from the Copernicus Data Space Ecosystem Browser (2025).

# 4 Clutha River flow data and analysis

Water level readings and gaugings to measure streamflow have been made at Clutha at Balclutha monitoring stations (NIWA site 75207) since 1952. The location of the site is shown on Figure 2-1. The maximum flow and mean flow for each year is shown on Figure 4-1. Orange circles indicate years where surveys from some or all cross sections were provided by ORC. There was a period with several very high flows between 1994 and 1999.

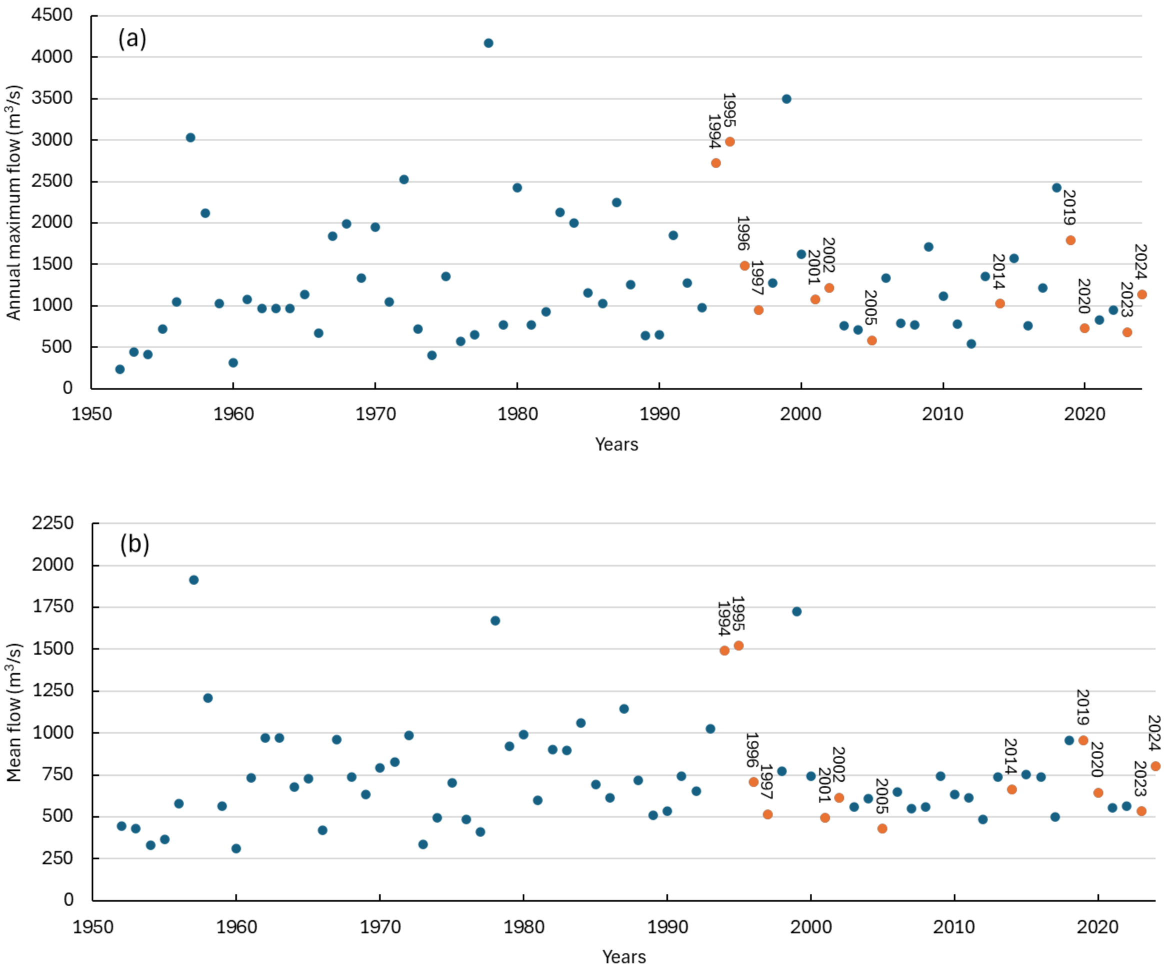



**Figure 4-1: Annual maximum flow (a) and mean flow (b) for the Clutha River at Balclutha monitoring site.**

A "stage for flow" analysis uses time-series data of flow gaugings made at the Balclutha water level recorder (NIWA site 75207). These data are collected to determine rating curves which relate the height of the water surface (the stage) to the corresponding river flow in cubic metres per second. While rating curves are made to allow calculation flow from a measured water level, they may be used in reverse to calculate how water level has changed, over the years. An increase in water level could be due to increased vegetation and other types of flow resisting roughness such as debris and bed-forms, or it could be due to morphological changes such as aggradation (rising) of the riverbed. In either case, if over time there is an increase in the stage for a given flow this is an indication that freeboard and flood capacity is decreasing.

# 5 Results

## 5.1 Bed level changes

### 5.1.1 Mean bed level

Characteristically, mean bed level falls in the downstream direction and is lower where an alluvial channel narrows. Here, mean bed levels (as defined in section 3) show a consistent pattern over the years, being high around sections C5–C6, falling by around a metre at section C4, then rising again moving downstream by around 1.5 m, to be highest where the river bifurcates into the Matau and Koau Branches (Figure 5-1). The changes in mean bed level upstream of the bifurcation show no clear trend on this graph with variations roughly within a 0.6m range over the last 30 years. From the bifurcation downstream, the range in bed level variation increases, reaching around 0.8 m in the Matau branch (at section M11). At the bifurcation, the bed levels dip, typically remaining lower into the Koau Branch in most years and rising downstream into the Matau Branch in all surveyed years. The mean bed level of the most downstream section on the Matau Branch (M11) is higher than more upstream sections.

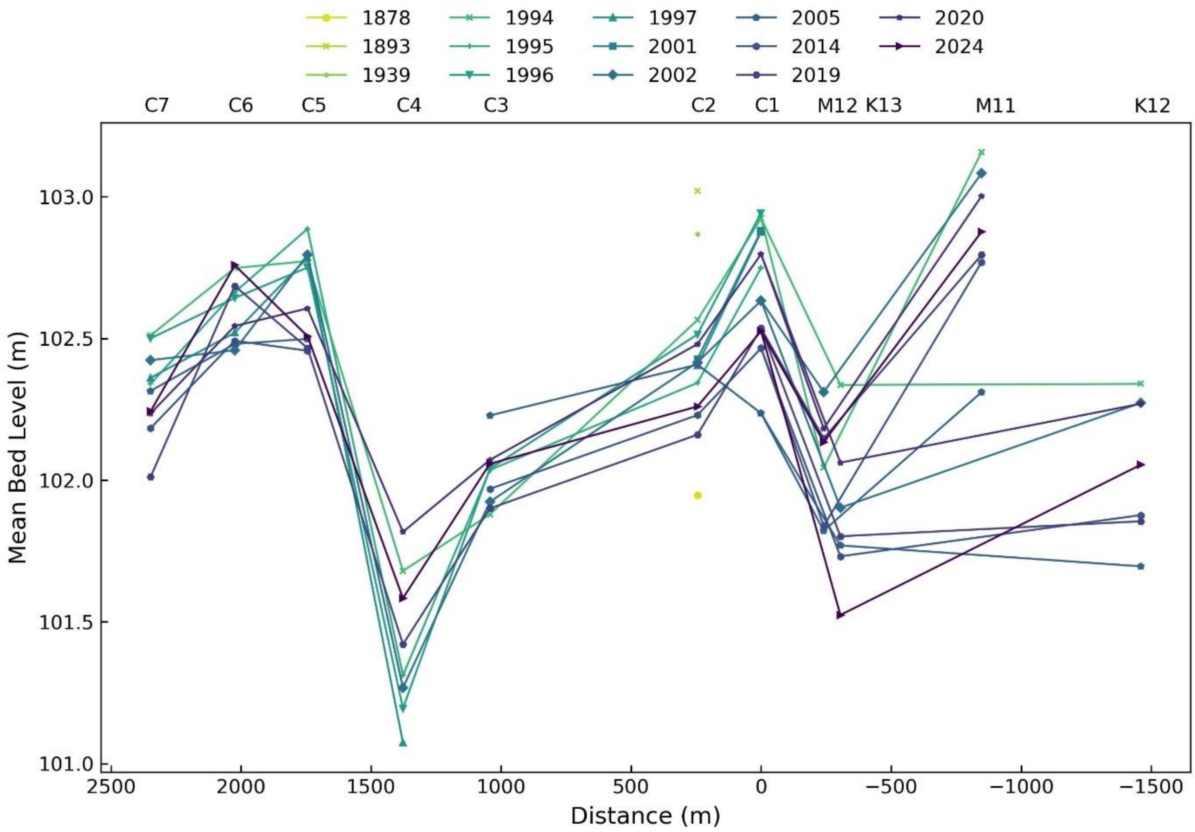



**Figure 5-1: Historical changes in the mean bed level (MBL) of the Clutha River near Balclutha township.** The x-axis shows river distances measured relative to cross-section C1 with positive distances representing upstream cross sections and negative distances downstream. Cross-section IDs are indicated at the top of the graph.

To better assess the temporal evolution of the bed level at each cross-section, mean bed level values were plotted against survey years (Figure 5-2). A linear regression line was fitted to each dataset to identify trends, and R-squared values were calculated to quantify how well the regression line explains variability in the data. All sections except C3, C4, C6, and M12 indicate a negative trend in mean bed level (i.e., lowering over the past 30 years). Sections C5 and C7, in particular, have higher $R^2$ values confirming significant riverbed degradation over time. At C5 and C7 the averaged mean bed level (the trendline value) has fallen by 0.35 m from the 1990s to the present day. Section K13 also shows degradation over time ($R^2$= 0.43) with 0.8 m decrease in averaged mean bed level.

At section C2, the first surveys (from 1878) show noticeable aggradation occurred before 1900. Conditions have since changed with land use and construction of the Roxburgh Dam and, if this early data is excluded, the section exhibits a clear negative trend in mean bed level over recent time, with an $R^2$ value of 0.85 (green line in Figure 5-2). A similar pattern is observed in cross-sections K12 and M11, where the exclusion of the 2005 survey—during which the middle bar was not surveyed—reveals mild riverbed degradation over time (green lines in Figure 5-2).

Sections M12, C3 and C6 do not display any significant trend in mean bed level and appear to have remained relatively stable over the analysed period. C4 shows a weak rising trend.

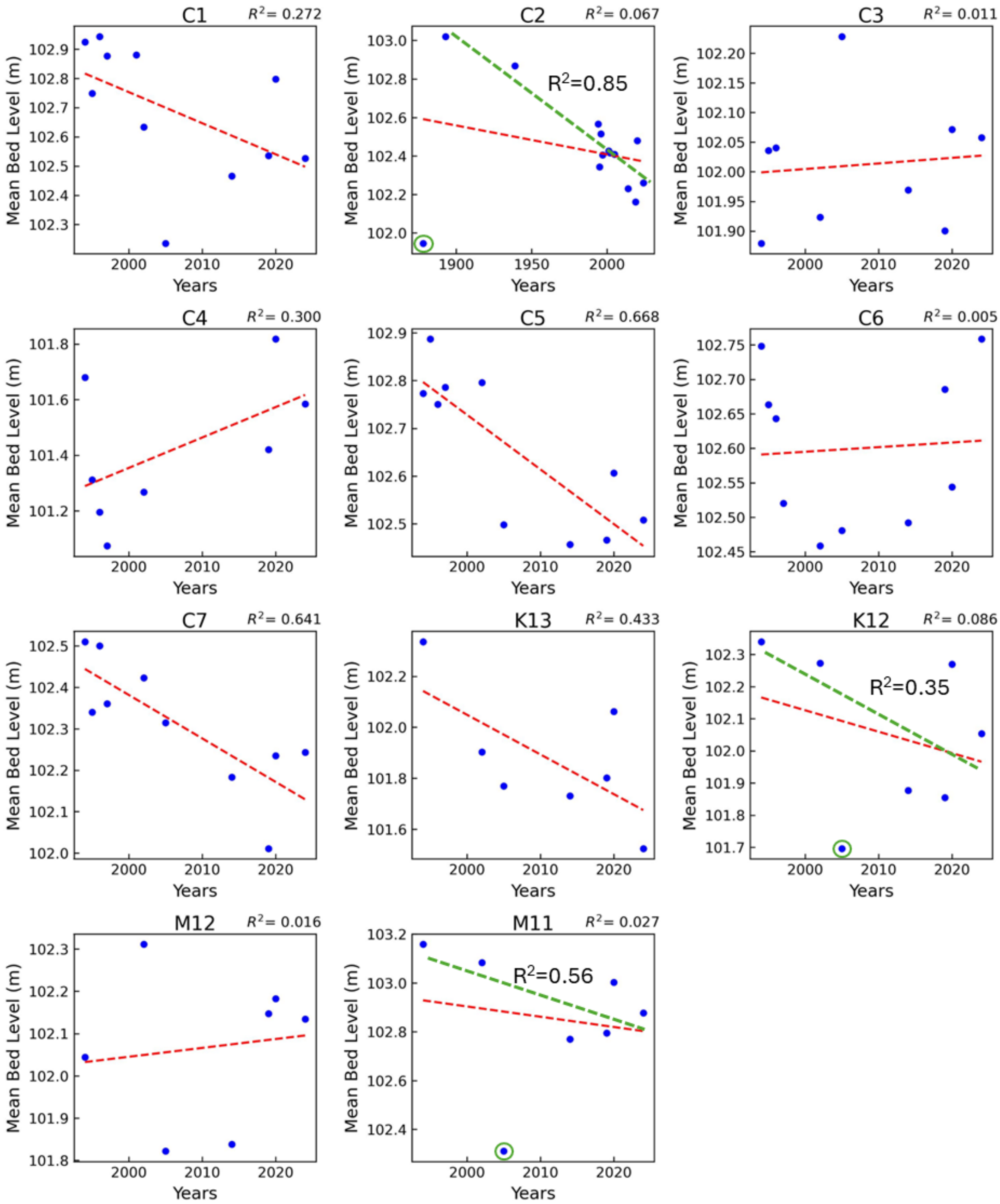



**Figure 5-2: Changes in the mean bed Level over years at each cross section.** The red lines indicate a linear regression trend for the years observed. The R-squared values for the regression lines, indicating the goodness of fit, are displayed in the top-right corner of each subplot. The green lines indicate linear regression trend after removing the outliers shown by green circles. For cross section C2, when the first survey in 1878 is ignored a strong trend of degradation in mean bed level is observed. For cross sections K12 and M11, the 2005 survey is ignored for the green line regression (part of the mid-river section was missing in the 2005 survey). Note that the axis scales differ on some plots.

Further analysis was conducted by averaging the mean bed level changes for each recent decade and comparing this with a 1990s baseline mean bed level (Figure 5-3). Following the period with very high flows from 1994 to 1999, bed levels generally fell below 1990 levels until the 2010s (blue and orange lines) then rose again in the 2020s (yellow line.) Except at C6, C4, C3 and M12, averaged levels are still below the 1990 levels. Section C4 has risen 0.4 m above the 1990 mean bed level.

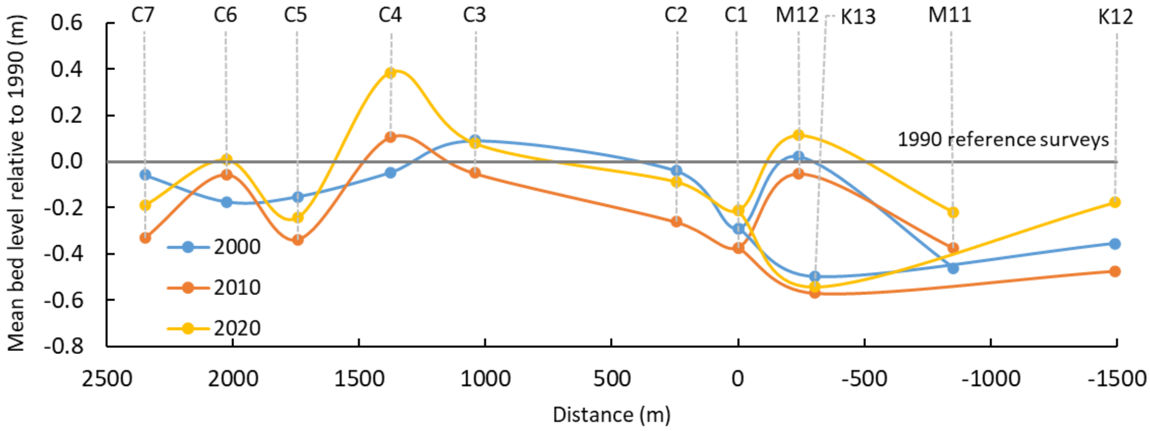
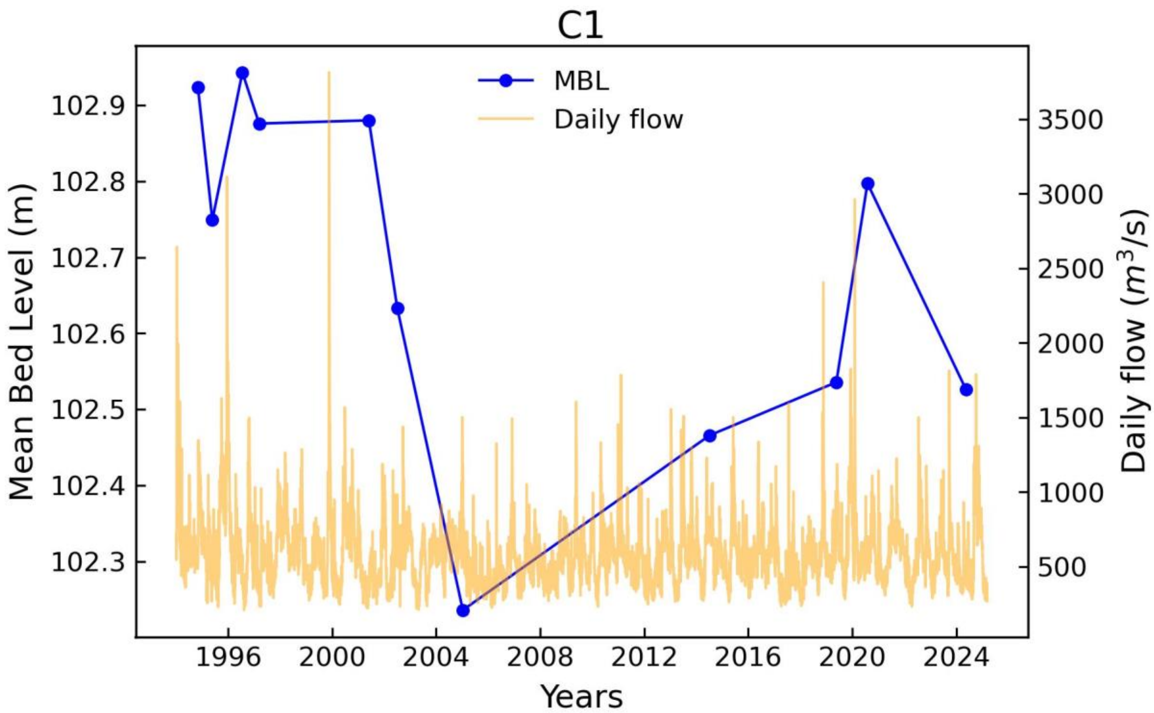



**Figure 5-3: Mean bed level change relative to 1990 in the Clutha River near Balclutha, with surveys grouped by decade.** The “1990” reference line represents combined surveys from 1990–1999, the “2000” line includes surveys from 2000–2009, the “2010” line covers surveys from 2010–2019, and the “2020” line represents surveys from 2020 onward. The x-axis shows river distances measured relative to cross-section C1 with positive distances representing upstream cross sections and negative distances downstream. Cross-section IDs are indicated at the top of the graph.

Changes in mean bed level over time were compared with mean annual flow and maximum annual flow. Examples are shown in Figure 5-4 for C1 and C6 with the remainder in Appendix C. There appears to be a tendency for the mean bed to rise when the flow rises but this not apparent at all cross sections and, at some sections, a reverse trend is evident, particularly after year 2020.



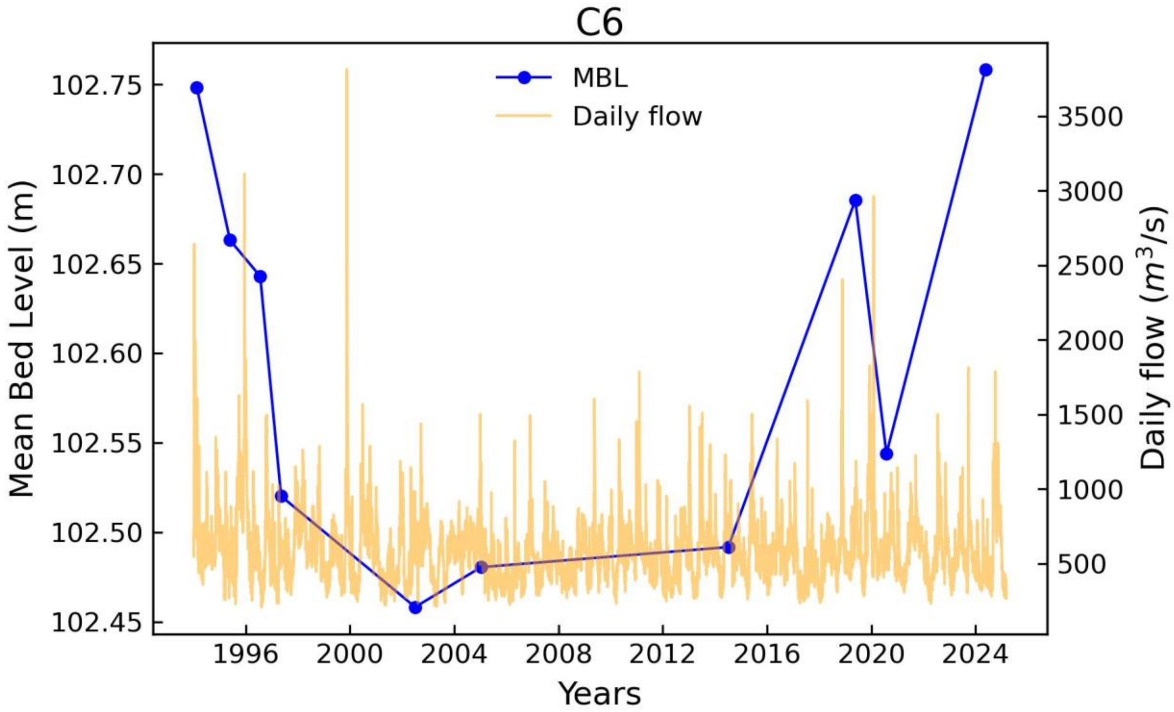



**Figure 5-4: Evolution of mean bed levels with time and daily mean river flow at section C1 and section C6.**

### 5.1.2 Minimum bed level

Changes in minimum bed levels are shown in Figure 5-5 with a separate line for each surveyed year. From cross section C6 to C4, the minimum bed level decreases in the downstream direction, reaching a low point around cross sections C3 and C4. Beyond this point, the bed level rises again in the downstream direction to cross-section C1. From C1, the minimum bed level falls moving down the Koau Branch (sections K13 and K12). For the studied cross sections, except for a high C1 level in 1994, the minimum bed level downstream in the Matau Branch is higher than at the upstream sections. The higher Matau Branch bed was also evident in the mean bed level analysis (Section 5.1.1).

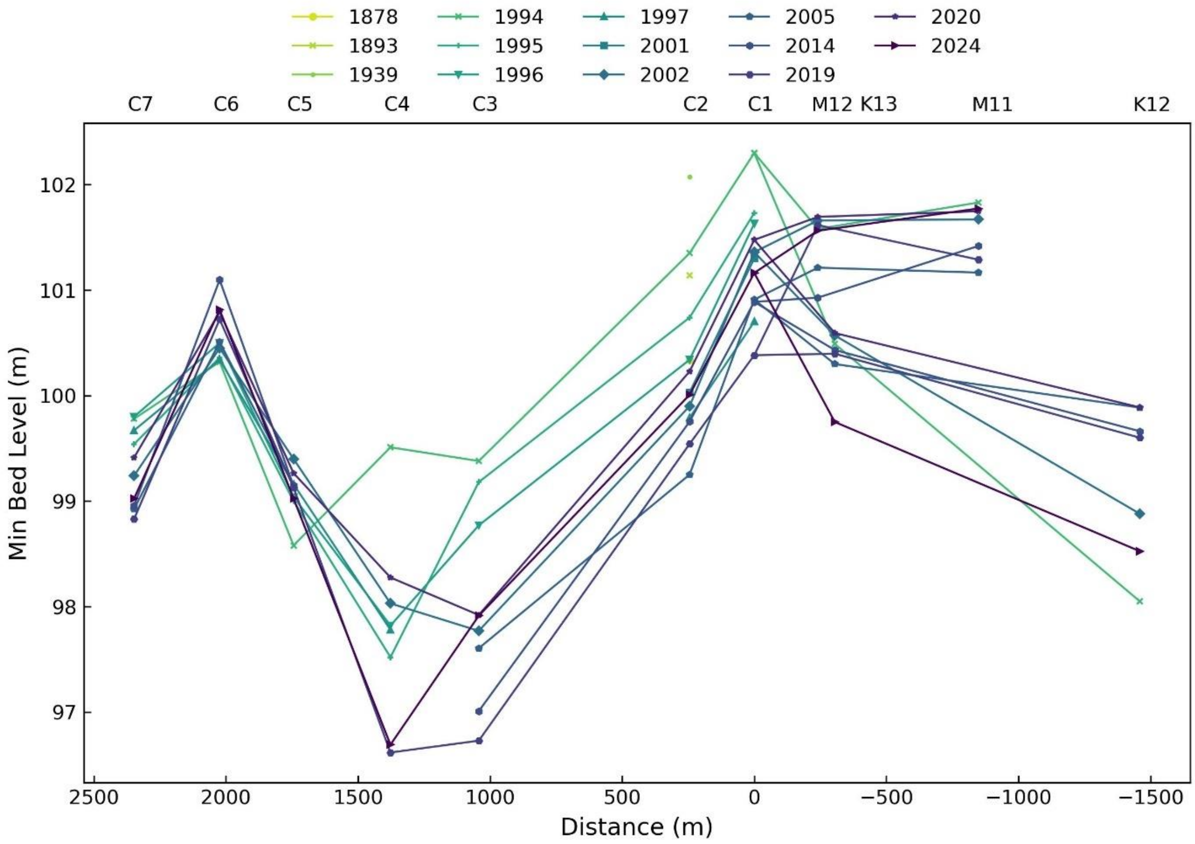



**Figure 5-5: Historical changes in the minimum bed level of the Clutha near Balclutha.** The x-axis shows river distances measured relative to cross-section C1 with positive distances representing upstream cross sections and negative distances downstream. Cross-section IDs are indicated at the top of the graph.

Trendline analysis for minimum bed levels is shown in Figure 5-6. While cross-section C6 exhibited no clear trend in **mean** bed level over time (Figure 5-2), the deepest point used to be on the true right side of the channel but is now in the centre (Appendix B). The **minimum** bed level shows a long-term rise in the deepest part of the river (Figure 5-6). These changes may be a result of historic, upstream river training works. Cross-section C3 similarly showed no discernible trend in mean bed level, but the minimum bed level indicated sustained erosion in the deepest portion of the channel, highlighting localized changes not captured by mean bed level analysis. Cross-section C7 displayed a consistent trend in minimum bed level that mirrored the overall changes observed in the mean bed level. The bed level changes at C7 are more uniform across the entire cross-section, affecting both the mean and minimum bed levels in a similar manner. Cross-section K13, on the Koau Branch, exhibited a similar pattern, with both the minimum and mean bed levels indicating recent deepening.

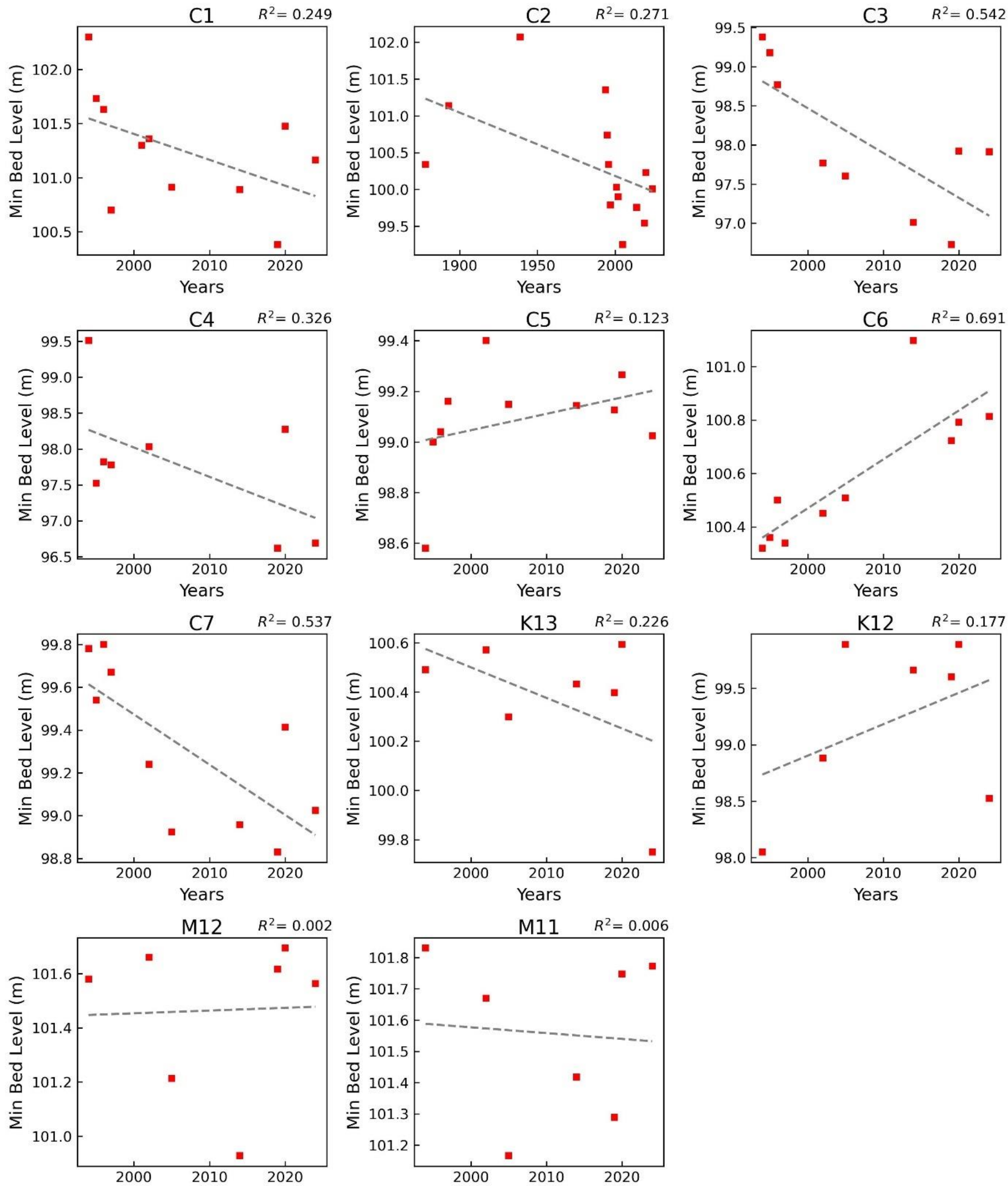



**Figure 5-6: Changes in the minimum bed Level over years at each cross section.** The dashed lines indicate the linear regression trend for the changes observed. The R-squared values for the regression lines are displayed in the top-right corner of each subplot. Note that the axis scales differ on some plots.

### 5.1.3 Average height above mean bed level

The area above mean bed level, divided by the total width, gives an average height of the part of the bed lying above mean bed level. This illustrates how much the bed level varies across a section. Changes in this parameter are plotted against downstream distance in Figure 5-7 for each surveyed year. Overall, there is a slight trend of decreasing bed level variation across a cross section, moving in the downstream direction towards the bifurcation.

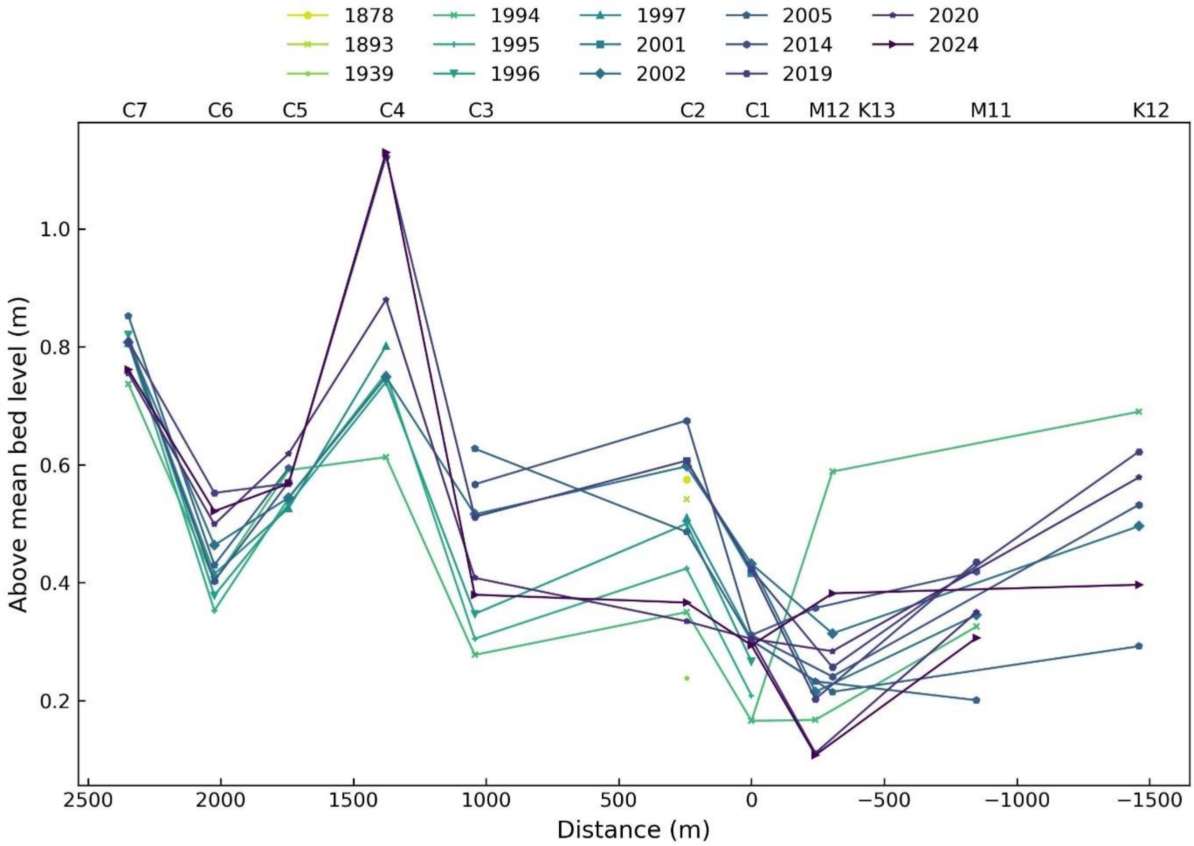



**Figure 5-7: Historical changes in the height above bed level values of the Clutha River near Balclutha.** The x-axis shows river distances measured relative to cross-section C1 with positive distances representing upstream cross sections and negative distances downstream. Cross-section IDs are indicated at the top of the graph.

The average height above mean bed level values show a clear increasing trend with time at cross sections C4 and C6, indicating an increase in the exposed (visible) area of the riverbed during low-flow conditions (Figure 5-8). Variation has increased significantly at section C4. This suggests the development or expansion of bars or deepening of low flow channels in these sections over time. In contrast, the height above mean bed level values at the other cross-sections did not exhibit any clear trends, implying minimal to no long-term changes in the bed forms.

There is no cross-section located on the large gravel bar between cross-sections C2 and C3 (located next to Kaitangata Highway and downstream of Ipswich Street. Therefore, it is not possible to quantify changes in the height of this significant bar.

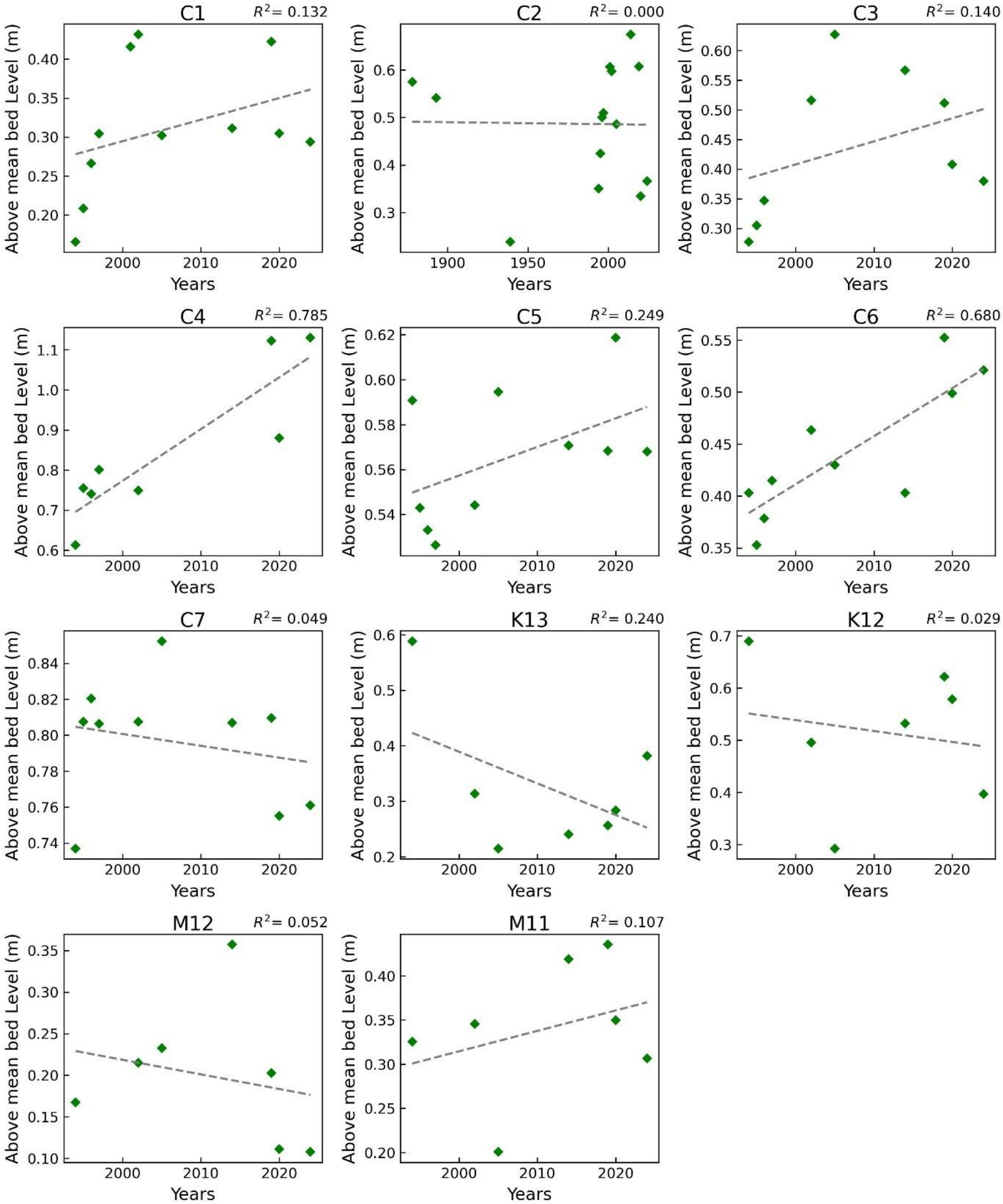



**Figure 5-8: Changes in the average height above mean bed level over years at each cross section.** The dashed lines indicate the linear regression trend for the changes observed. The R-squared values for the regression lines are displayed in the top-right corner of each subplot. Note that the axis scales differ on some plots.

## 5.2 Changes across individual cross sections

Considering the overlaid sections in Appendix B and parameter plots in Figures 5-2 to 5-6 we observe the following net changes moving from downstream to upstream:

- **Cross sections K12 and M11:** No clear trend of aggradation or degradation is evident over time based on the recorded survey data.
- **Cross section M12:** In the 1990s the section was relatively flat. The channel then deepened on the right side and raised on the left side of the centreline. By 2019, the channel had risen on the right side and by 2024 was again relatively flat. NIWA gauging comments indicate 10,000 cubic metres of gravel extraction occurred on the right bank and 8,500 cubic metres from the left bank of the downstream channel bifurcation over the period 17-Feb-2002 to 13-Mar-2002.
- **Cross section K13:** In the 1990s the section was high on the right bank of the main channel, but this bar was gone by 2002. The data then indicate low variation in bar height until 2020 when the channel deepens left of the main channel centreline and rises on the right bank of the main channel.
- **Cross section C1:** Over the last 10 years, a noticeable shift in the gravel bar located in the middle of the cross section is observed where the river splits into the two branches. The middle bar has migrated further to the right, resulting in increased bank erosion along the true left bank.
- **Cross section C2:** Being near the railway bridge, this cross section has the longest survey record, dating back to 1878. Between the first recorded survey in 1878 and the second in 1893, the riverbed experienced up to 2 m of aggradation across the cross section. By 1939, deposition of up to 1.5 m occurred towards the right bank, while scouring of up to 2 m was observed on the left bank. Between 1939 and the present day, slow degradation has dominated across the entire channel width.
- **Cross section C3:** Between 1994 and 2024, this cross section experienced periods of shifting in the middle bar and channel, along with phases of channel deepening (1994–2019) followed by significant aggradation (2019–2024). The middle bar rose approximately 2.3 m from 1994 to 2005, reaching its maximum recorded height. However, from 2005 to 2024, gradual erosion of the middle bar occurred, with about 1.1 m of bar height lost.
- **Cross section C4:** This section showed gradual scouring along the true left bank and deeper parts of the channel, while deposition was observed along the true right bank. Between 1994 and 2024 the deeper section of the channel experienced scouring of up to 3 m, whereas up to 2.1 m of sediment deposition occurred along the right bank.
- **Cross section C5:** A gradual degradation trend was observed from 1994 to 2024, accompanied by localized sediment accumulation along a small section of the true right bank between 185 to 220 m cross section distance.
- **Cross section C6:** Different patterns of change were observed across this cross section. Both the true left and right banks experienced deposition, whereas the mid-channel deepened. From 1994 the middle section of the cross section (between 100 m and 200 m) experienced a rise of up to 1.5 m by 2024. The true left bank (between 200 m and 250 m) rose up to 3 m, while the right bank (between 0 m and 80 m) experienced 1.1 m of rise. Overall, mean bed level degraded until 2002 then aggraded back to the 1994 level by 2024.

- **Cross section C7:** Scouring was observed at the true left bank between 1994 and 2024. The deeper section of the channel experienced erosion from 1994 to 2019, followed by deposition between 2019 and 2024.

## 5.3 Satellite imagery

Overhead imagery can reveal positions and sizes of channels and bars in a river. Examples are shown in Figure 5-9. Seven selected images, captured between 2016 and 2025, are presented in Appendix D. Interpretation of bar size and shape is not straightforward, as river flow was not the same when the images were captured.

A noticeable change occurred between 2016 and 2025 with the movement of the gravel bar on the right bank, just before the Clutha River splits into the Matau and Koau branches. In the 2016 imagery, this bar intersects the railway bridge and extends across both C1 and C2 cross sections. The bar shape evolves, and by 2025, has disappeared. From 2020 a new bar develops on the opposite bank, and by 2025 it has fully formed at the tip of Inch Clutha (Figure 5-9).

The location of the mid-river bar between cross sections C2 and C3 has remained relatively stable over the years.

The long, thin, right-bank bar extending from C4 to C5 is stable over the years and becomes progressively more vegetated until by 2025 it resembles a river berm.

Due to variations in river flow at the time of satellite captures, it is not possible to measure quantitative temporal changes in the size of the bars, on the basis of the imagery. Bar size is also discussed in Section 6-2.


**Figure 5-9: Satellite imagery of the Clutha River at Balclutha on two dates: January 10, 2016 (left) and January 27, 2025 (right).** Imagery from Sentinel-2 satellite data. Red lines indicate the cross section locations. The flow monitoring site is shown with a magenta dot.

## 5.4 Flow data analysis

A NIWA flow recorder has operated at Balclutha since 1952. The gauging cross-section was located near river cross-section C3 until 2007 when it was moved 180 to 250 m upstream of the previous cableway location.

### 5.4.1 Minimum bed level

Up until 2010, the maximum water depth was recorded at the time of a NIWA gauging. Subtracting max. water depth from the stage (water surface elevation) gives the minimum bed level at the time of the gauging. The minimum bed levels from gauging data are shown in orange on Figure 5-10 below. After 2007, NIWA changed to jet boat ADCP gauging 180 to 250 m upstream of the previous cableway and recording of maximum water depth was subsequently discontinued. The gauged upstream bed depths are shown in bright red on Figure 5-11. Also shown are the ORC cross section survey minimum bed levels at section C3 (from Figure 5-6). An abrupt rise in minimum bed level occurred during the 1957 November flood when the thalweg level was raised by the flood. From the 1970's to the present the minimum bed level at section C3 has been getting lower.

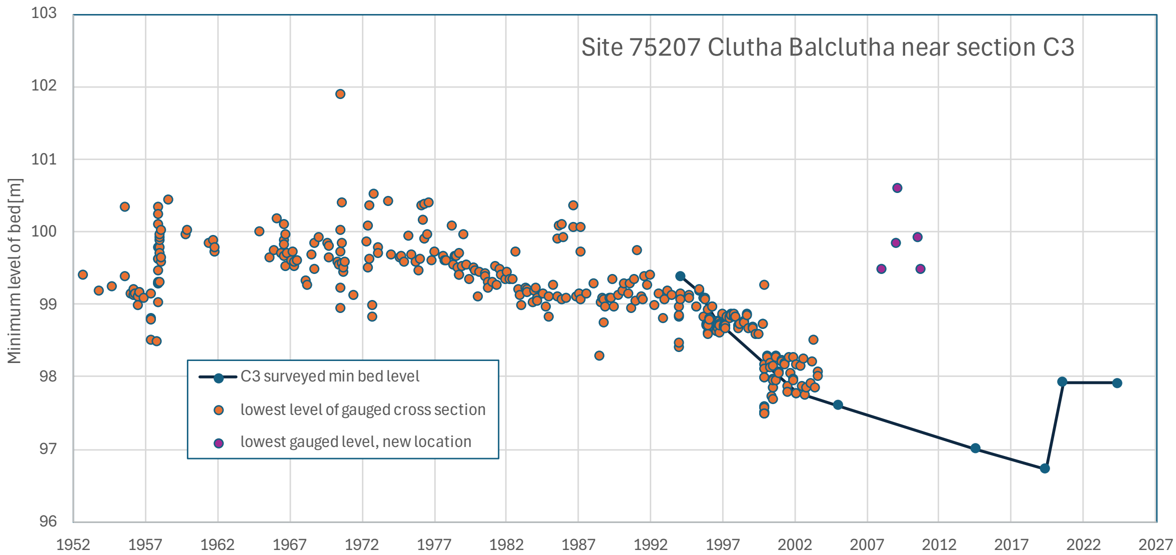



**Figure 5-10: Minimum bed level at times of flow gaugings near section C3.** Gauging data after 2007 (bright red dots) apply 180 to 250 m upstream of the previous cableway location.

### 5.4.2 Stage for flow results

Figure 5-11 shows the differences between measured water levels and what they would have been with no changes in the river bed since 1952 (i.e., no changes in the rating curves since 1952). Figure 5-12 shows differences in water levels compared to what they would have been with the December 1978 rating curve. While individual gaugings are made at different flows, and it is not meaningful to interpret every little change in these graphs, the graphs reveal any overall, long-term trends.

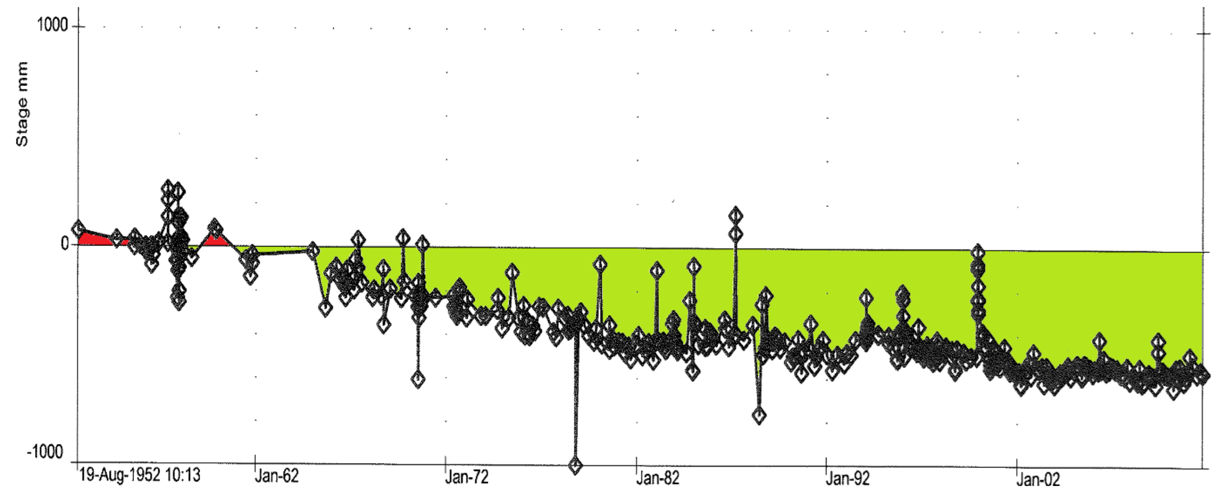



**Figure 5-11: Stage for flow compared with preservation of 1952 bed levels.**

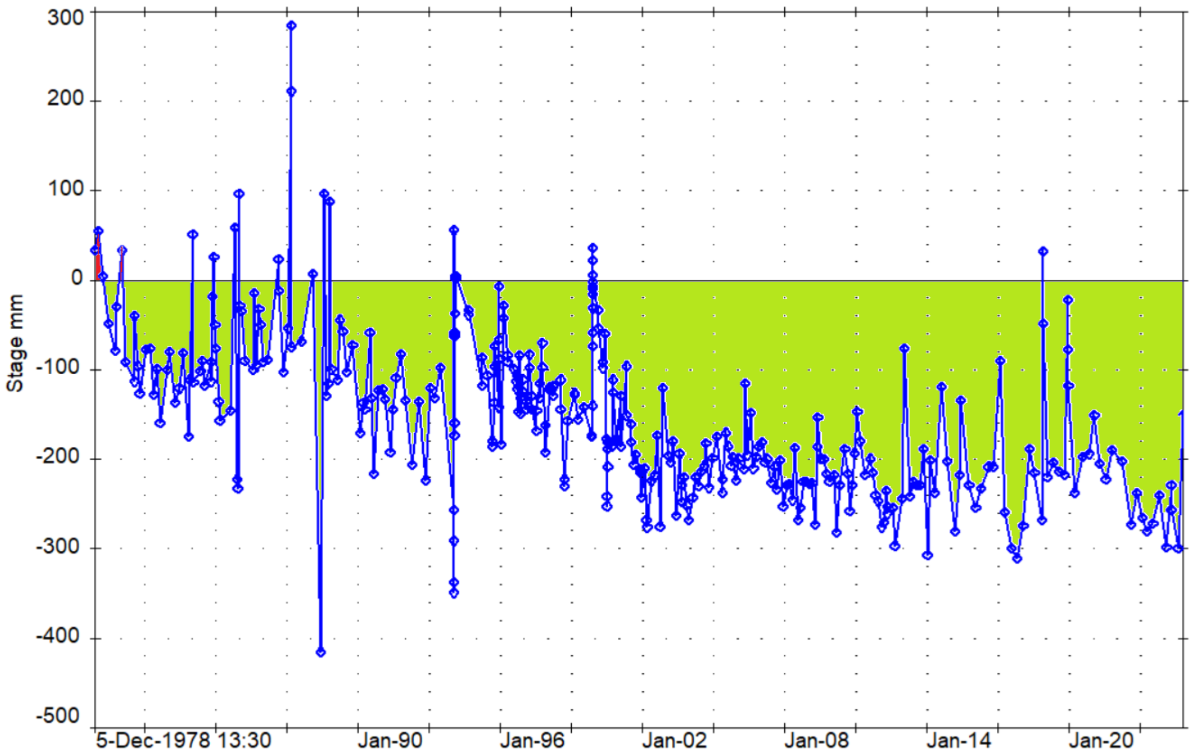



**Figure 5-12: Stage for flow compared with preservation of 1978 bed levels.**

According to these plots, water levels fell gradually from 1952 to be about half a metre lower by 1982. From 1983 to mid-2000 the levels oscillated with no net trend, then dropped approx. 0.2 m to reach another quasi-stable state for the most recent 20-year period.

Further information on water level trends at all measured flows can be found by comparing rating curves from gaugings made at different times. In Figure 5-13, flow gaugings are compared for three decades: 1952–1961, 1990–1999 and 2015–2024. Flows as low as 38.3 $m^3$/s occurred in the early record as Roxburgh Dam was filling in 1956. The lowest gauged flow was 50.3 $m^3$/s. In the middle decade there were several high floods (between 1994 and 1999). Figure 5-13 shows that in the 1990's flows up to 3000 $m^3$/s occurred at a lower stage than in the 1950's. In the most recent decade flows up to around 1500 $m^3$/s occurred at a lower stage than in the 1990's. This indicates channel deepening or reducing flow resistance over the decades. For very high flood flows[1], the flood stage increased relative to the 1990's but, up to 3000 m$^3$/s, remains lower than in the 1950's. While moderate floods indicate deepening of the channel, the recent, slight increase in stage of very high floods indicates possible constriction, raising or roughening of floodplains downstream of the gauging station.

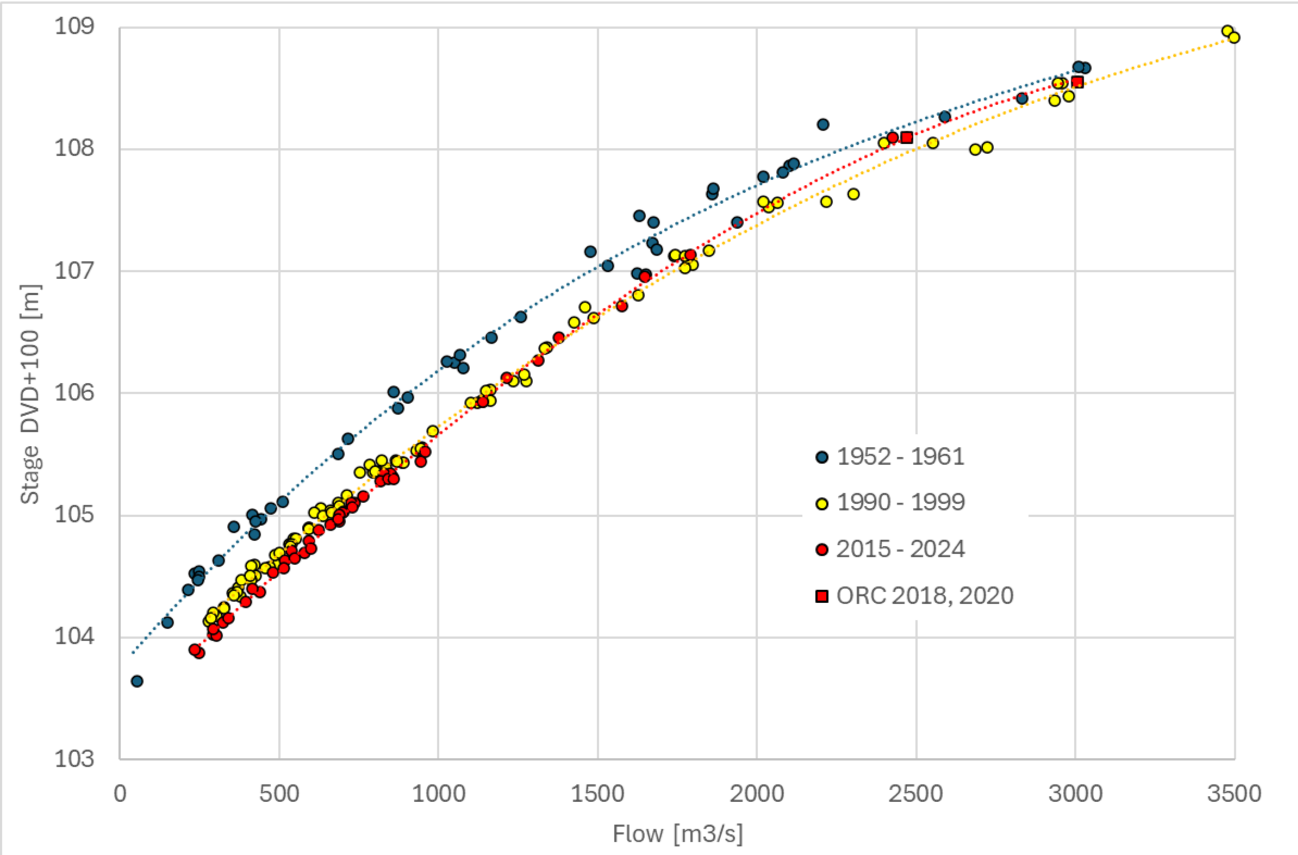



**Figure 5-13: Comparing stage for flow data from gauging measurements over the years.** Curves show three decades: 1952–1961, 1990–1999 and 2015–2024. Vertical axis is Dunedin Vertical Datum 1958 + 100 m.

[1] The two highest gaugings in 2015–2024 were made upstream of the NIWA rating site and adjusted by ORC to allow for the 2.5 km interdistance.

# 6 Discussion

## 6.1 Determine whether there is a significant trend in riverbed levels

Cross sections C1, C2, C5, C7, M11 and K12 show a clear degradational trend from the 1990's to the present. In particular, mean bed levels at C5 and C7 have fallen by around 0.35 m. Sections C3 and C6 do not display any significant trend in mean bed level and appear relatively stable over the analysed period. C4 shows a weak rising trend.

## 6.2 Assess changes in gravel bars or islands

The average height-above-mean-bed-level analysis indicates the vertical range in bed levels at measured cross sections. Changes in average height-above-mean-bed-level can indicate development or decay of channel bars. Over the surveyed years 1994 to 2024, there is a trend of increasing level variation at C4 and C6 but no noteworthy trend at other sections. Moving in the downstream direction, there is a slight general trend of decreasing bed level variation across the cross sections, which would suggest lower or flatter bars moving downstream past Balclutha.

Satellite imagery reveals a noticeable change between 2016 and 2025 with the movement of a gravel bar on the right bank, just before the Clutha River splits into the Matau and Koau branches. In the 2016 imagery, this bar intersects the railway bridge and extends across both C1 and C2 cross sections. The bar shape evolves, and by 2025, has disappeared. From 2020 a new bar develops on the opposite bank, and by 2025 it has fully formed at the tip of Inch Clutha. No net effect is evident in the C1 and C2 area above mean bed level plots. There is no cross-section located on a large gravel bar between cross-sections C2 and C3 (located next to Kaitangata Highway and downstream of Ipswich Street). Considering different flow rates at times of the satellite imagery, this bar appears stable over the 2016–2025 period.

## 6.3 Identify factors driving changes observed

In general, observed changes correspond to the expected long-term, morphological change following a severe reduction in sediment input (i.e., Roxburgh Dam construction). Bed levels and water levels have initially fallen and the rate of degradation appears to have tailed off with time. Recent reports that gravel bars are more evident at Balclutha may be due to the bar movement noted above and the fact that a stable bar can become more visible and appear to be higher if the river level falls alongside the bar. There has been a clear change in shape at section C6 (Appendix B). The deepest point (thalweg) used to be in the channel on the true right but is now in the centre. Historic aerial imagery below Figure 6-1) shows that between 1946 and 1995, mid-channel river training works narrowed and re-directed the channel upstream of C6. These works are likely to be the explanation for the thalweg movement at C6. There were also river training works to re-narrow the entrance to the Matau branch in the early 1970's [Retrolens.co.nz: air photos of 27/2/1968 and 28/2/1975].


**Figure 6-1: Aerial photographs from 1946 (left) and in 1995 (right). Blue line indicates the mid-channel river training works upstream of cross section C6.**

## 6.4 Evaluate whether observed riverbed level changes are sufficient to reduce flood capacity

Unless there is a strong overall trend, the interpretation of temporal changes in cross sections' effect on flood capacity is not straight-forward because a wide shallow section will not convey the same flow as a deep narrow section of equivalent area (or having the same mean bed level between bank benchmarks). Furthermore, flood levels at Balclutha can depend on conditions further downstream. While hydraulic modelling was beyond the scope of this study, the stage for flow analysis of gauging data provides reliable indications of changes in flood capacity at the NIWA gauging site near section C3. The gauging data from 1952 show water levels fell gradually from 1952 to be about half a metre lower by 1982. From 1983 to mid-2000 the levels oscillated with no net trend, then dropped approx. 0.2 m to reach another quasi-stable state for the most recent 20-year period. In the 1990's, flows up to 3000 $m^3$/s occurred at a lower stage than in the 1950's. In the most recent decade flows up to around 1600 $m^3$/s occurred at a lower stage than in the 1990's. This implies channel deepening (locally or downstream) or reducing flow resistance over the decades.

The relatively flat river gradient means changes in flood water levels at the NIWA gauging site will be reasonably representative of general changes in Clutha river levels alongside Balclutha and we can presume that flood capacity has not reduced. That said, the most recent flood gauging of 2425 $m^3$/s in October 2018 was at a slightly higher level than similar floods in the 1990s. Also, local changes in cross sections may re-direct currents against a bank with associated local superelevation and potential overtopping.

While a few of the Clutha cross section surveys were made during floods, an earlier model study (Smart and Bind 2006) noted that significant scour was required to pass historic floods at the flood levels observed at Balclutha. The required scouring was not evident in post-flood surveys. This indicates that temporarily scour may occur around the C3 location during a rising flood with the bed refilling as the flood falls. The extent of such flood scour is unknown but, assuming this has not reduced due to coarsening of the bed sediment size, historic behaviour does not indicate a reduction of flood capacity in the Balclutha reach.

# 7 Conclusions

The cross section data suggest a general long-term trend of lowering of the riverbed from the 1950s to about 2002 with less trend evident since 2002. This is consistent with the river adjusting to a reduction in bed load coming from upstream following commissioning of the Roxburgh hydro dam in 1954. Mean bed level analyses show that ten of the eleven cross sections are stable or degrading. Section C4 (at the State Highway Bridge) shows a weak rising trend in mean bed level. Minimum bed levels are stable or falling at all cross sections except C6 (North end of Elizabeth Street) where the surveyed low point is rising with time due to previous river training works. Cross sections C4 and C6 are the only sections which show any trend in growth or expansion of bars or deepening of low flow channels over time. Channel flood capacity depends not only on the cross section, but also hydraulic roughness and downstream slope. These effects are captured by flood gauging measurements. Analysing the gaugings at Balclutha, since 1952, shows channel capacity is increasing for floods up to around 1600 $m^3$/s.

Recent reports that gravel bars are now more evident at Balclutha may be due to the fact that a stable bar will become more visible and appear to be higher, if the river level falls alongside the bar. A field inspection may be able to shed light on this possibility.

Factors which could affect these conclusions are:

- Bed scour during a rising flood and deposition on a falling flood may mask the true cross section during a flood peak. The extent of such flood scour is unknown at Balclutha but, assuming this has not reduced due to coarsening of the sediment size (bed armouring), the studied cross section surveys do not indicate reduction in flood capacity of the Balclutha reach.

- The effect of any gravel mining on cross section evolution has not been quantified but any enduring effects have been captured by the cross section surveys.

Ongoing monitoring and, in particular, flow gauging during future high floods, is strongly recommended. This would help quantify the degree of bed scour induced by floods, which will improve future hydraulic modelling of the river.

# 8 Acknowledgements

Survey data and funding for these analyses were provided by the Otago Regional Council.

# 9 References


Copernicus Data Space Ecosystem. Copernicus Data Space Ecosystem Browser. European Commission. Retrieved February 21, 2025, from https://dataspace.copernicus.eu/

Grant, G. E., Fassnacht, H., McClure, E. M., Klingeman, P. C. (2003) Downstream effects of the Pelton-Round Butte hydroelectric project on bedload transport, channel morphology, and channel-bed texture, lower Deschutes River, Oregon. Water Science and Application, 7, 175-176.

Hicks, D.M., Walsh, J.M., Duncan, M.J. (2000) Clutha River Sediment Budget. NIWA Client Report CHC00/45.

Otago Regional Council (2008) Channel morphology and sedimentation in the Lower Clutha River. ISBN: 1-877265-59-4

Smart, G.M., Bind, J. (2006) Clutha Delta flood protection. NIWA Client Report: CHC2006-021. Project: ORC06504, February 2006.

# Appendix A Corrections made to historic cross section data

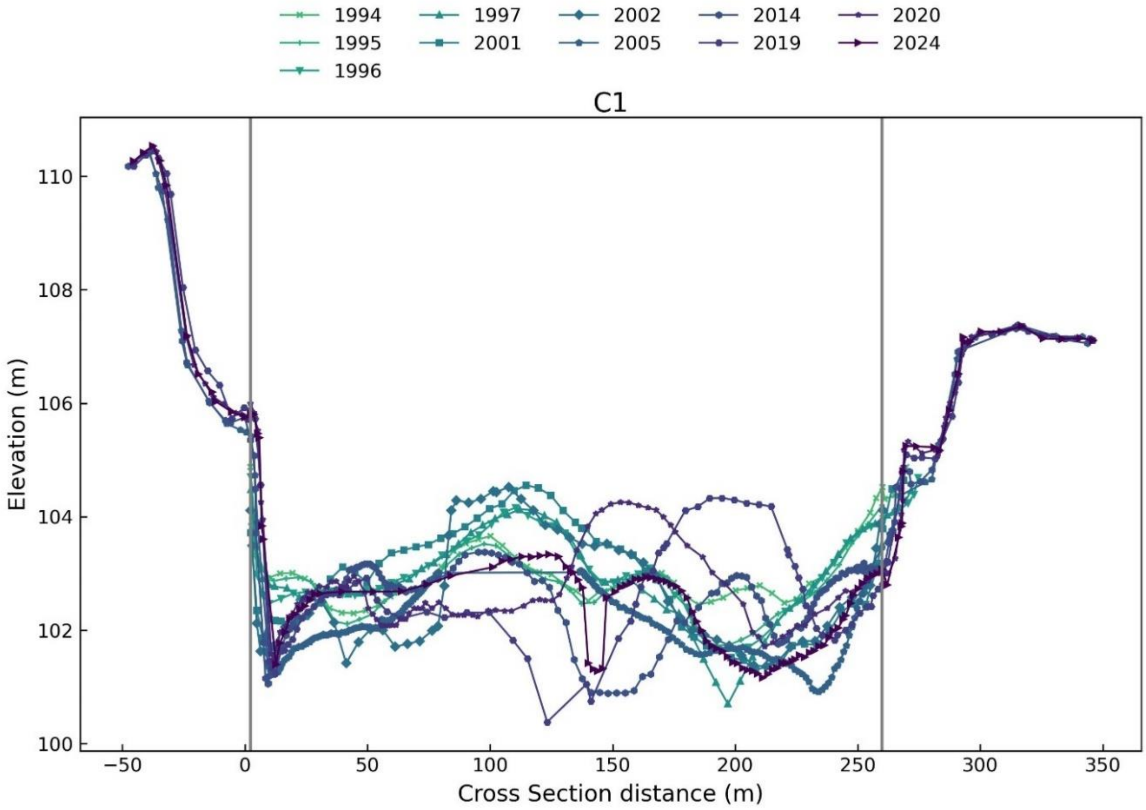
**Table A-1: Adjustments applied to align historic cross section survey data.**

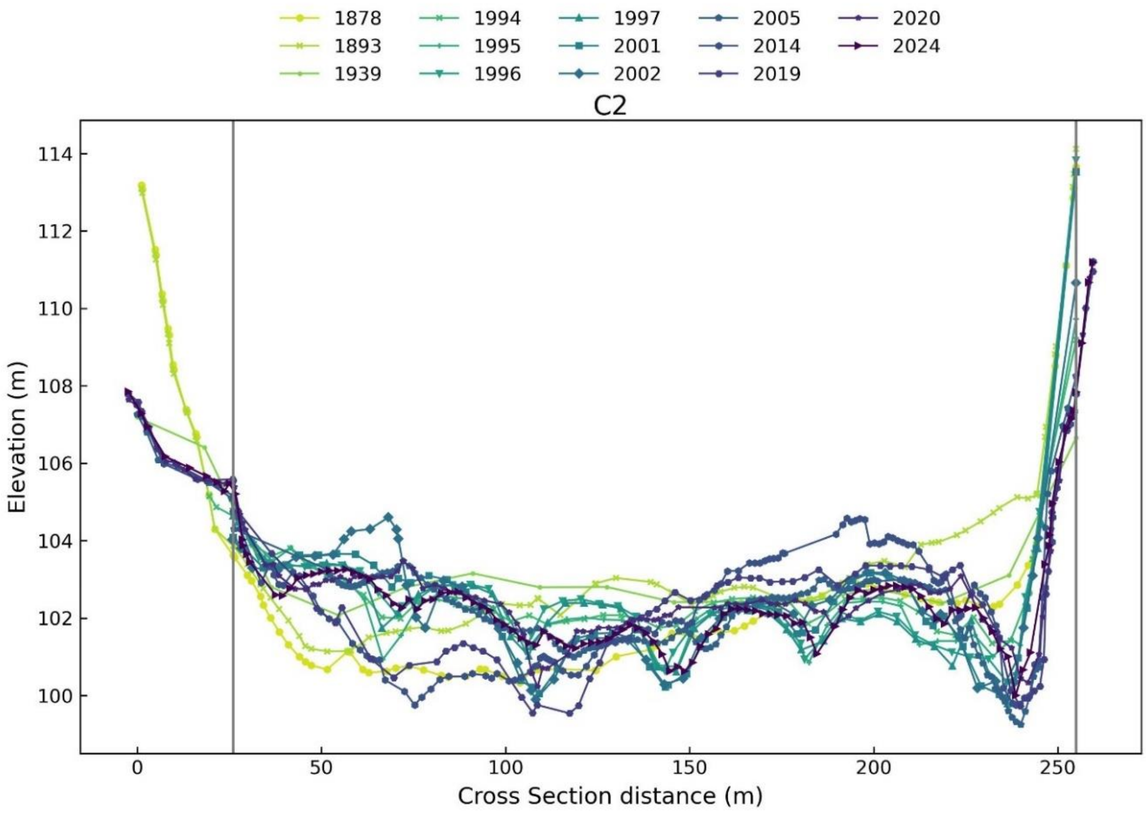
| Cross section ID | Surveyed Year | Horizontal offset applied | Comments on surveys with incomplete or unreliable data |
|---|---|---|---|
| C1 | 1996 | Shifted 10 m to right | |
| | 1997 | Shifted 9.1 m to right | |
| | 2001 | Shifted 12 m to right | |
| | 2002 | Shifted 12.2 m to right | |
| | 2019 | Shifted 37 m to left | |
| | 2020 | Shifted 37 m to left | |
| | 2023 | Shifted 37 m to left | Unreliable data - ignored in bed level change analysis |
| | 2024 | Shifted 37 m to left | |
| C2 | 2023 | | Unreliable data - ignored in bed level change analysis |
| C3 | 1994 | Shifted 6.9 m to right | |
| | 1995 | Shifted 6.9 m to right | |
| | 1996 | Shifted 6.9 m to right | |
| | 2002 | Shifted 6.9 m to right | |
| | 2023 | | Unreliable data - ignored in bed level change analysis |
| C4 | 2019 | Shifted 37 m to left | |
| | 2020 | Shifted 37 m to left | |
| | 2023 | Shifted 37 m to left | Unreliable data - ignored in bed level change analysis |
| | 2024 | Shifted 37 m to left | |
| C5 | 2019 | Shifted 26 m to left | |
| | 2023 | | Unreliable data - ignored in bed level change analysis |
| K12 | 2005 | | Incomplete cross section data (up to 159 m distance) - ignored in bed level change analysis |

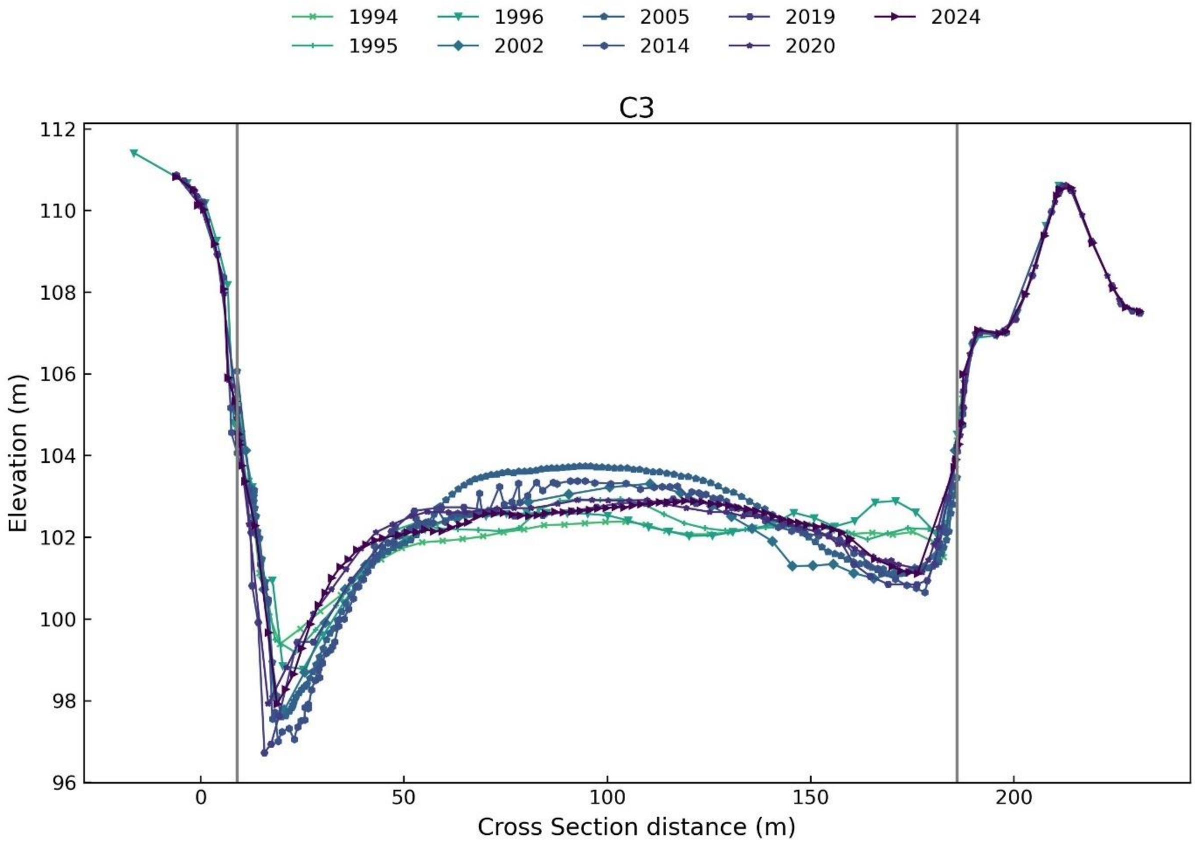
| Cross section ID | Surveyed Year | Horizontal offset applied | Comments on surveys with incomplete or unreliable data |
|---|---|---|---|
| | 2020 | Shifted 26 m to left | |
| | 2023 | Shifted 26 m to left | Unreliable data - ignored in bed level change analysis |
| | 2024 | Shifted 26 m to left | |
| M11 | 2005 | | Incomplete cross section data (middle section between 25 to 64 m is missing) - ignored in bed level change analysis |
| | 2023 | Shifted 10 m to right | |

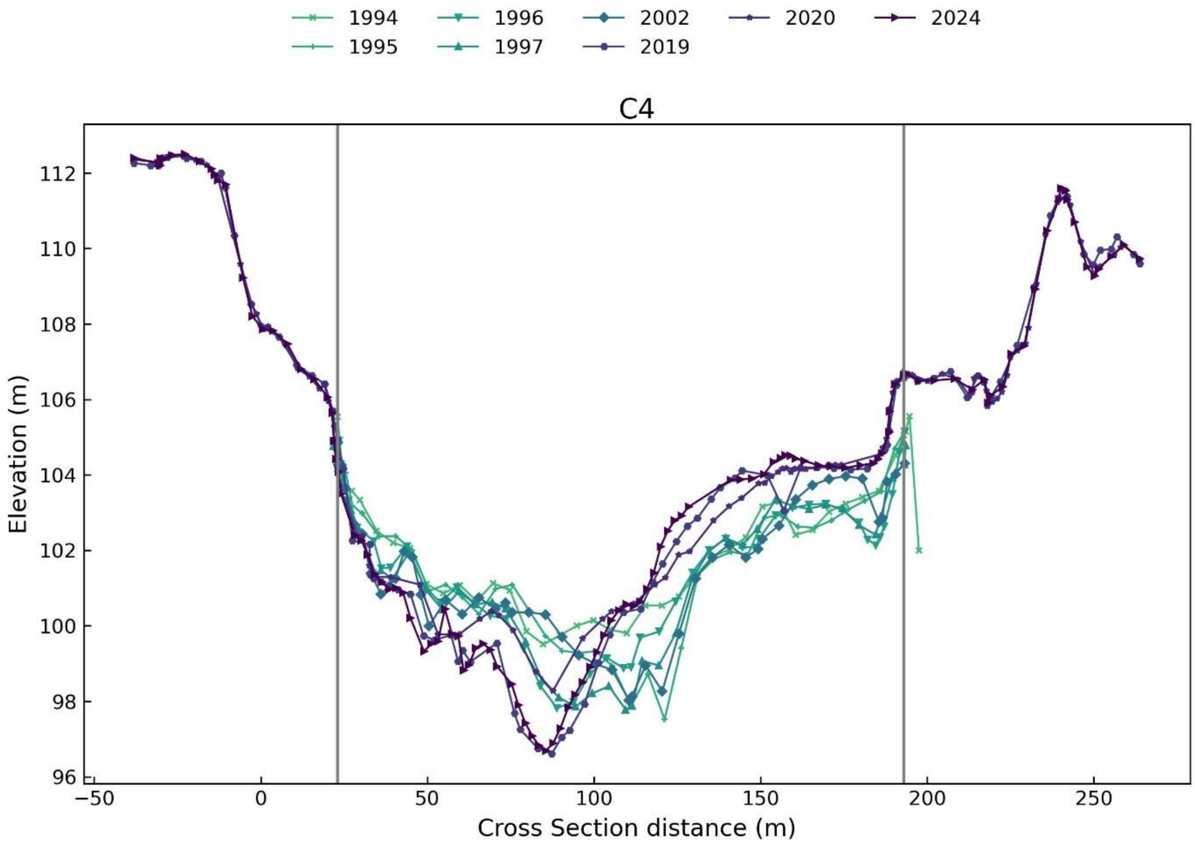
## Appendix B Cross section profiles for surveyed years

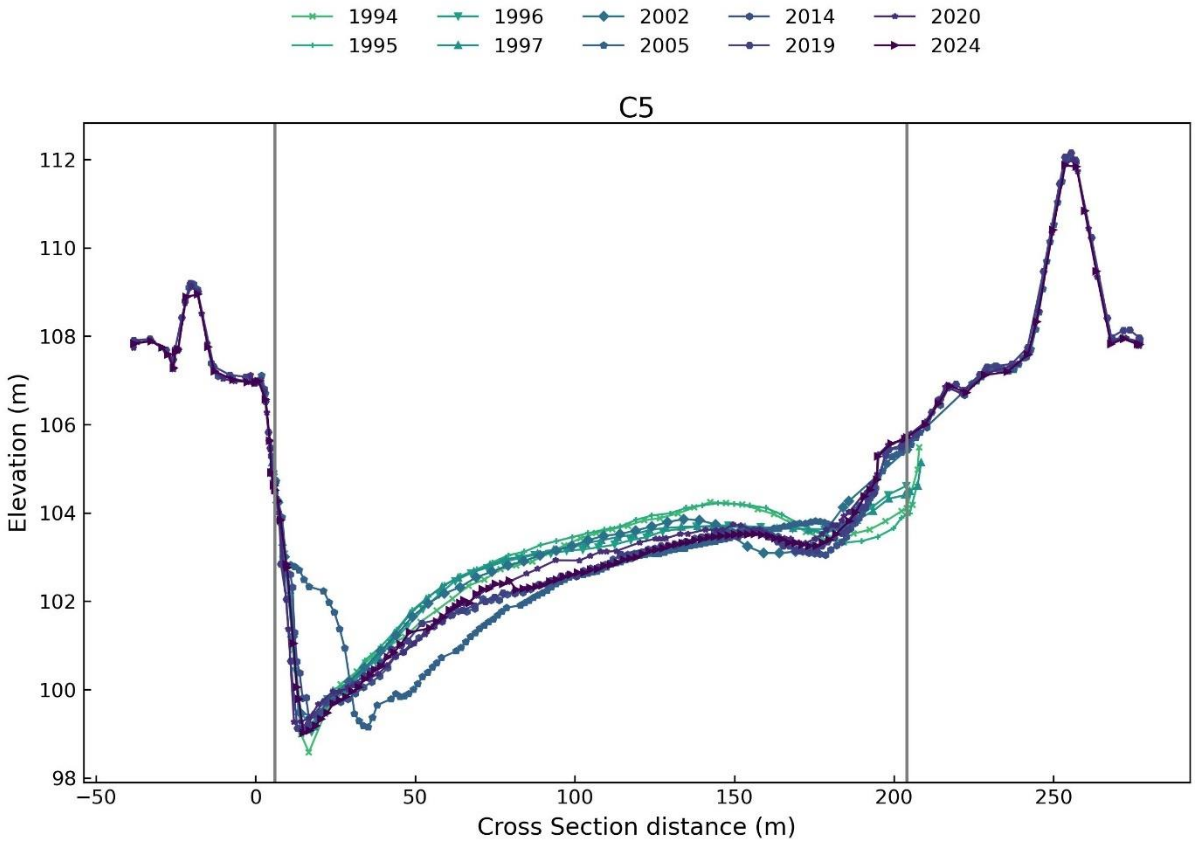
All cross sections are viewed looking downstream.



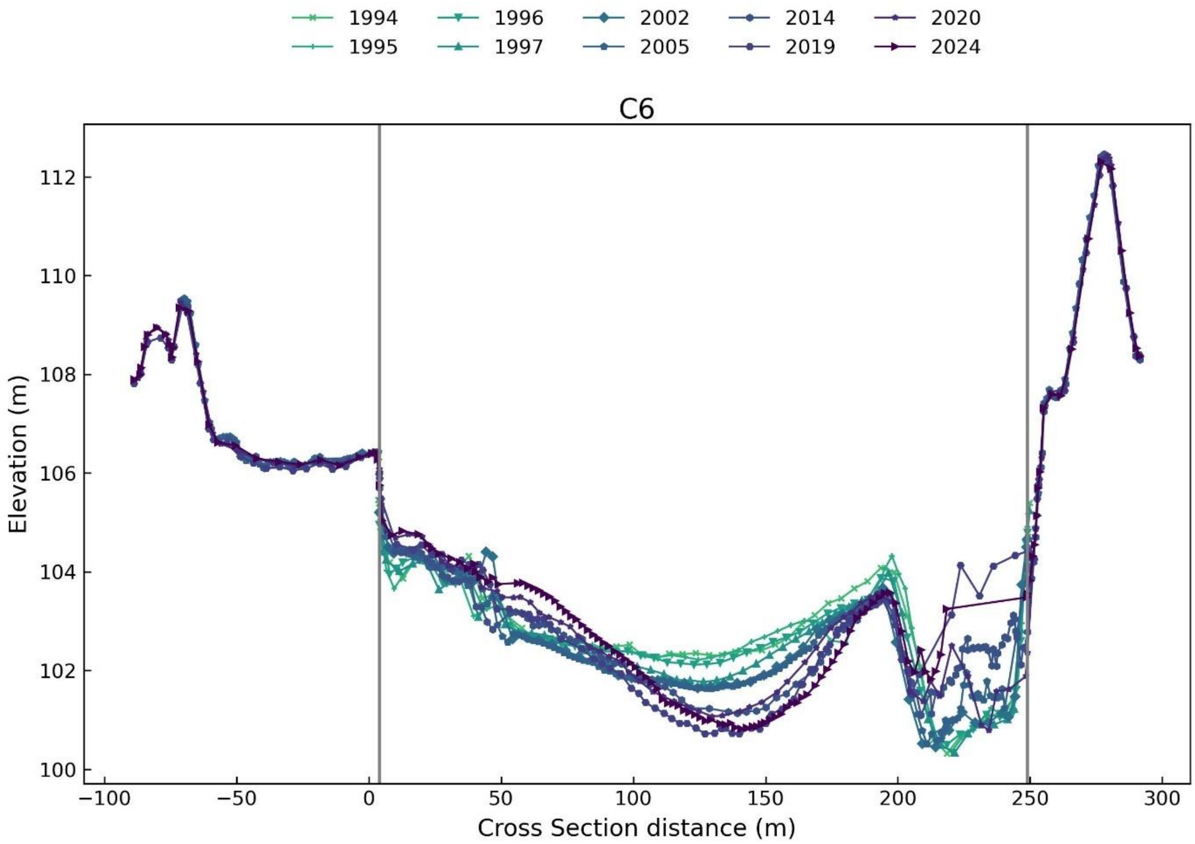




1994
1995
1996
2002
2005
2014
2019
2020
2024
C3
Elevation (m)
Cross Section distance (m)

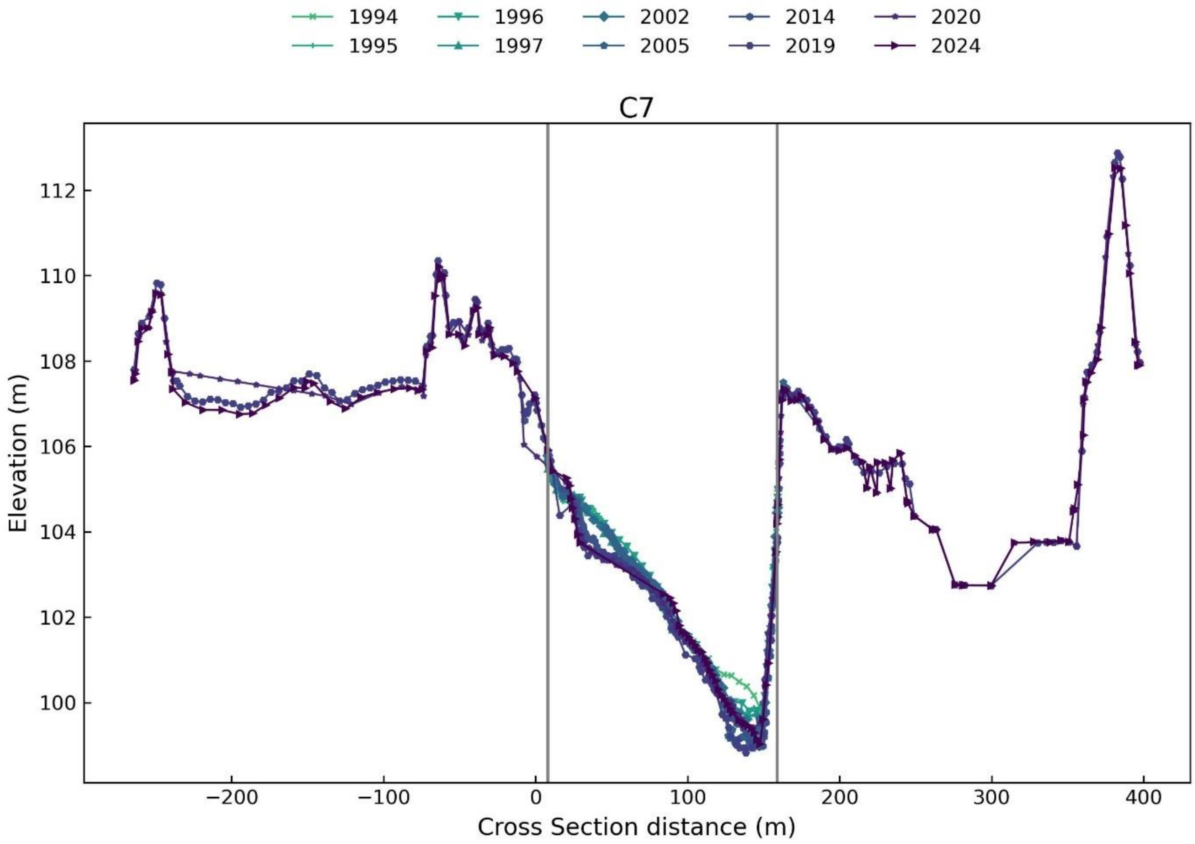

1994
1995
1996
1997
2002
2019
2020
2024
C4
Elevation (m)
Cross Section distance (m)

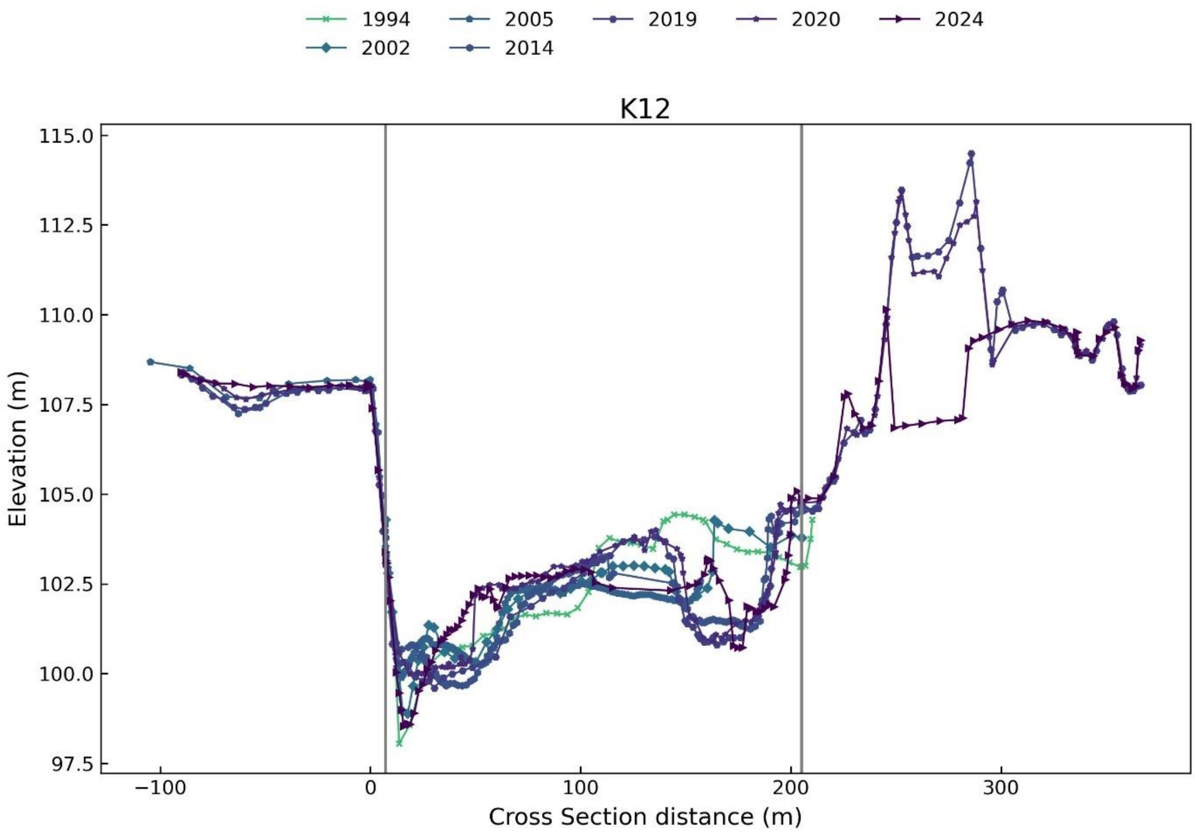


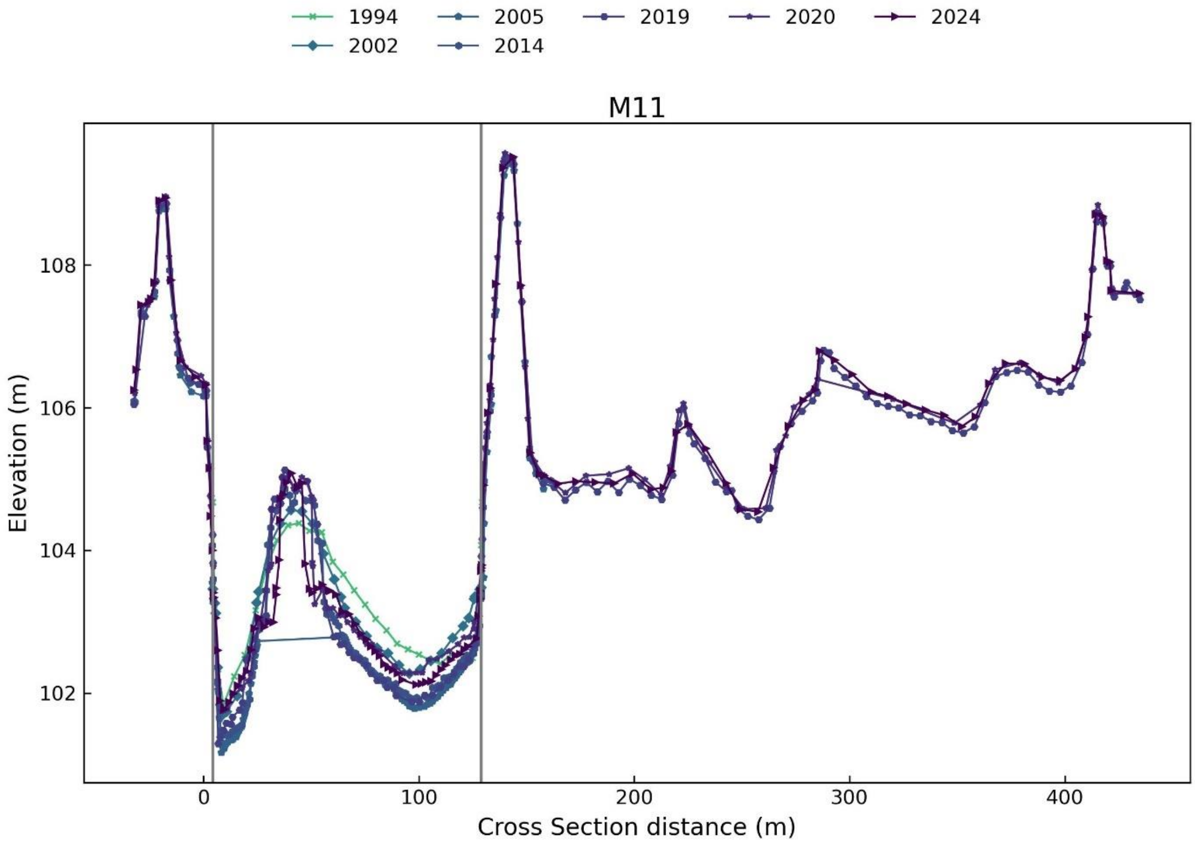
1994
1996
2002
2014
2020
1995
1997
2005
2019
2024
C5
Elevation (m)
Cross Section distance (m)

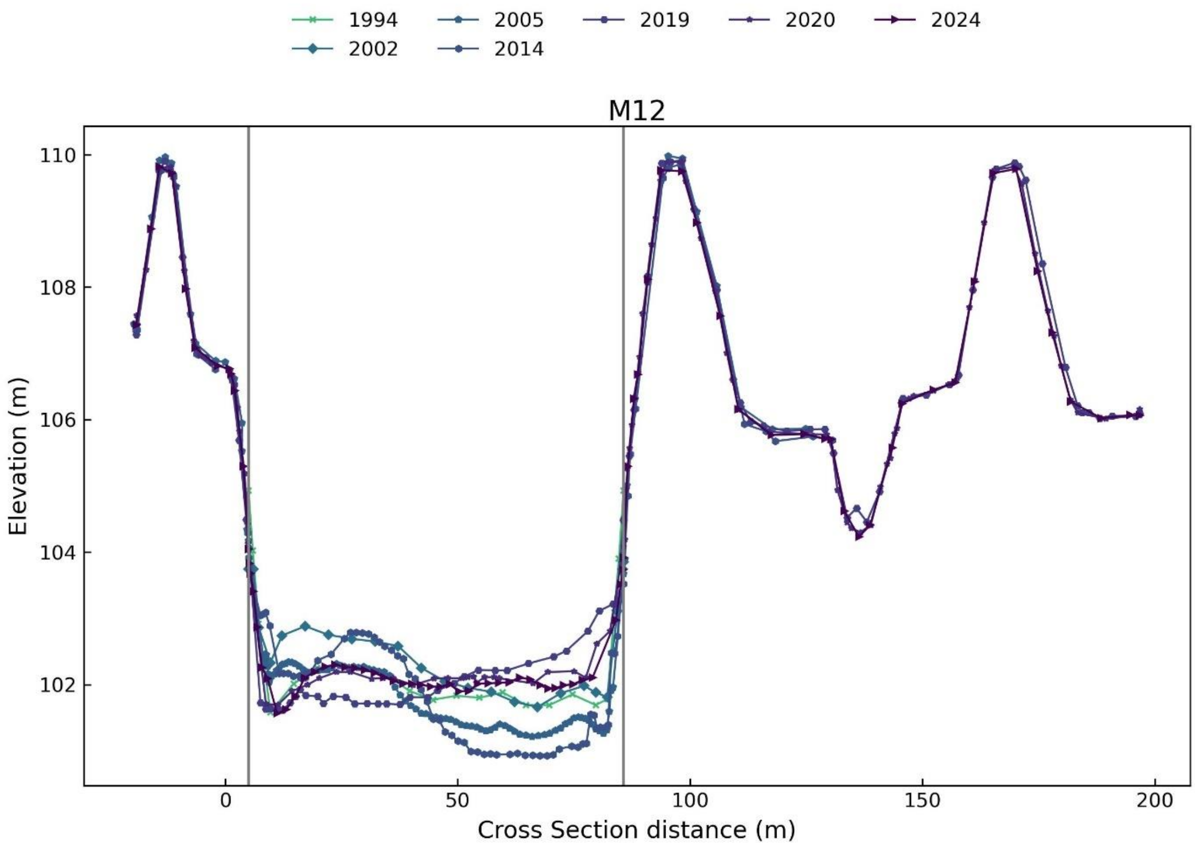



1994
1996
2002
2014
2020
1995
1997
2005
2019
2024
C6
Elevation (m)
Cross Section distance (m)


1994
1995
1996
1997
2002
2005
2014
2019
2020
2024
C7
Elevation (m)
Cross Section distance (m)
112
110
108
106
104
102
100
−200
−100
0
100
200
300
400


1994
2002
2005
2014
2019
2020
2024
K12
Elevation (m)
Cross Section distance (m)
115.0
112.5
110.0
107.5
105.0
102.5
100.0
97.5
−100
0
100
200
300


1994
2005
2019
2020
2024
2002
2014
M11
Elevation (m)
Cross Section distance (m)
0
100
200
300
400
102
104
106
108


1994
2005
2019
2020
2024
2002
2014
M12
Elevation (m)
Cross Section distance (m)
0
50
100
150
200
102
104
106
108
110

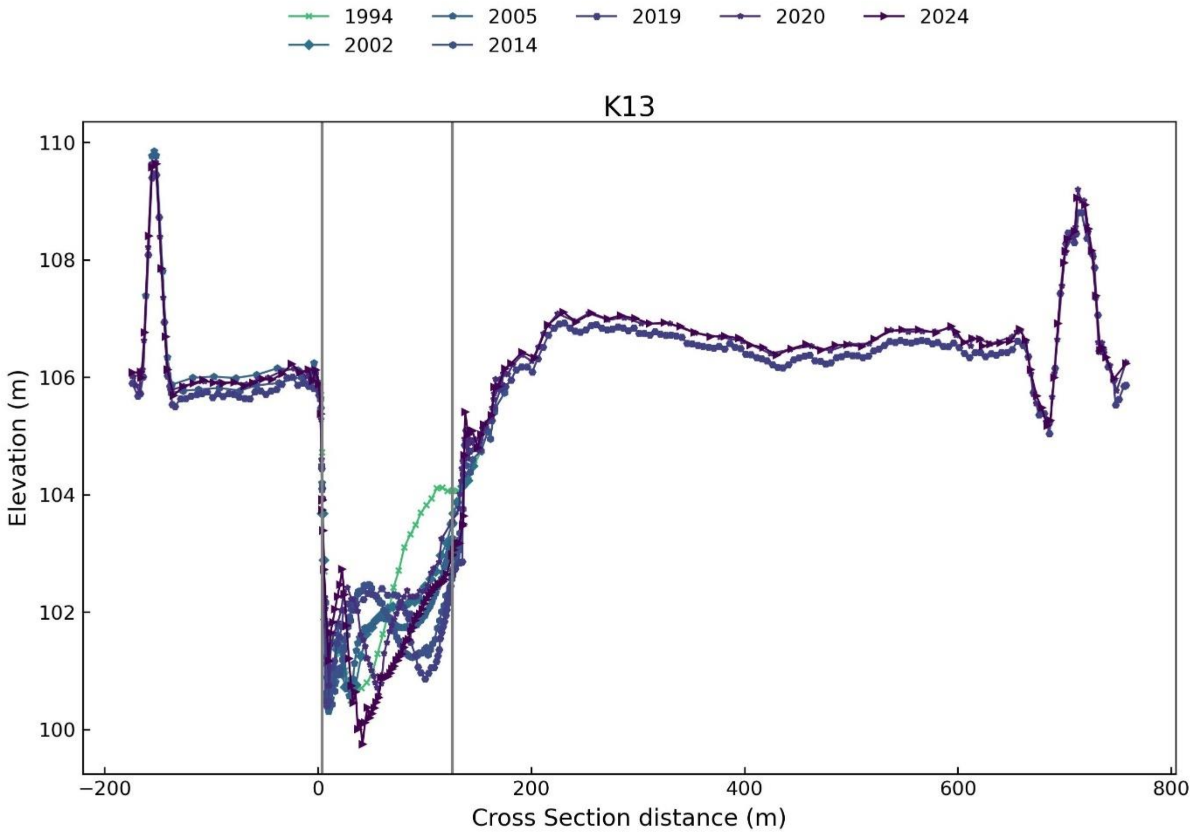
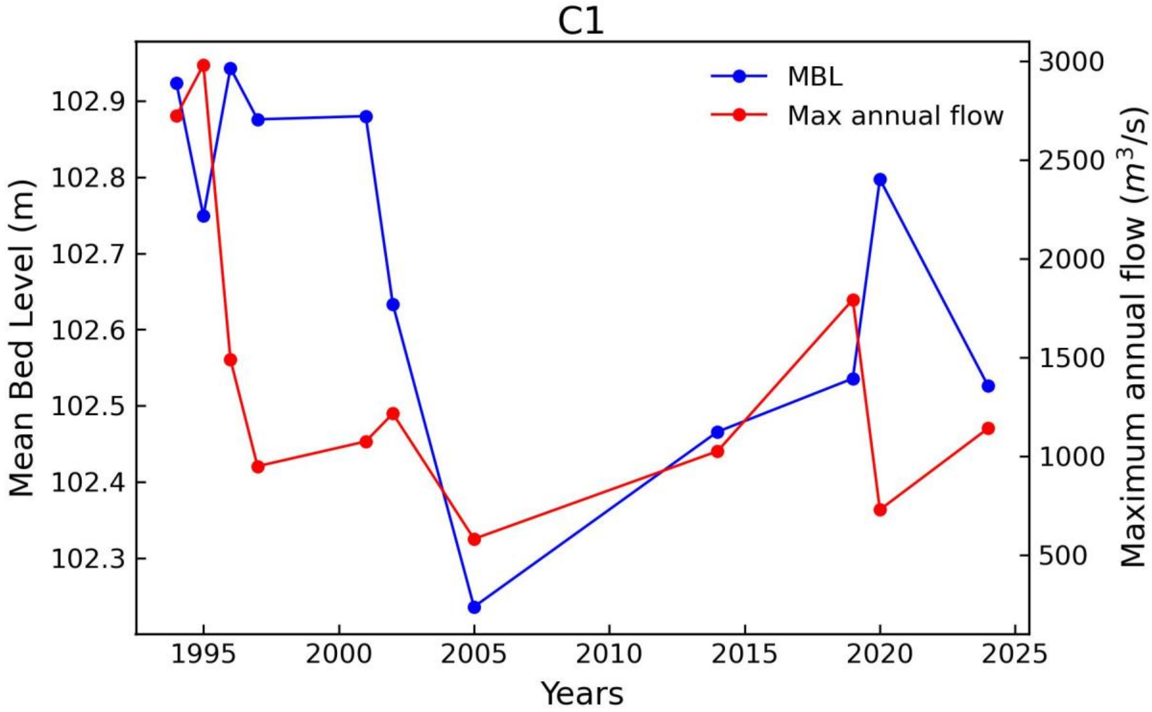
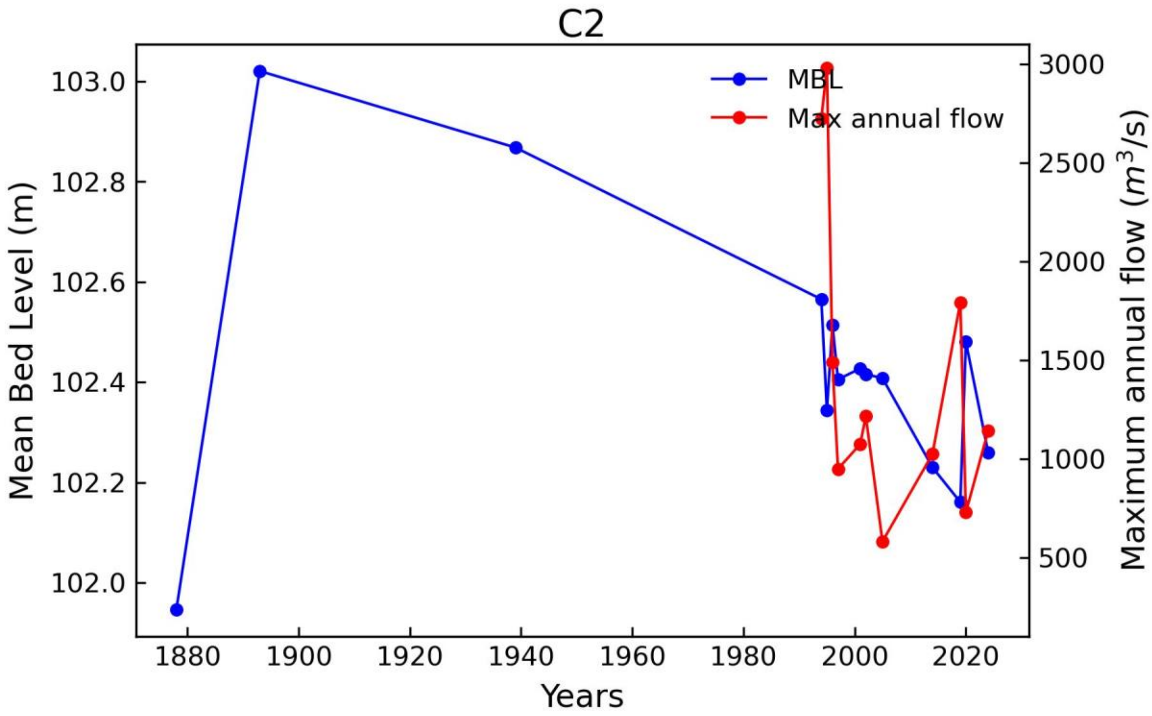


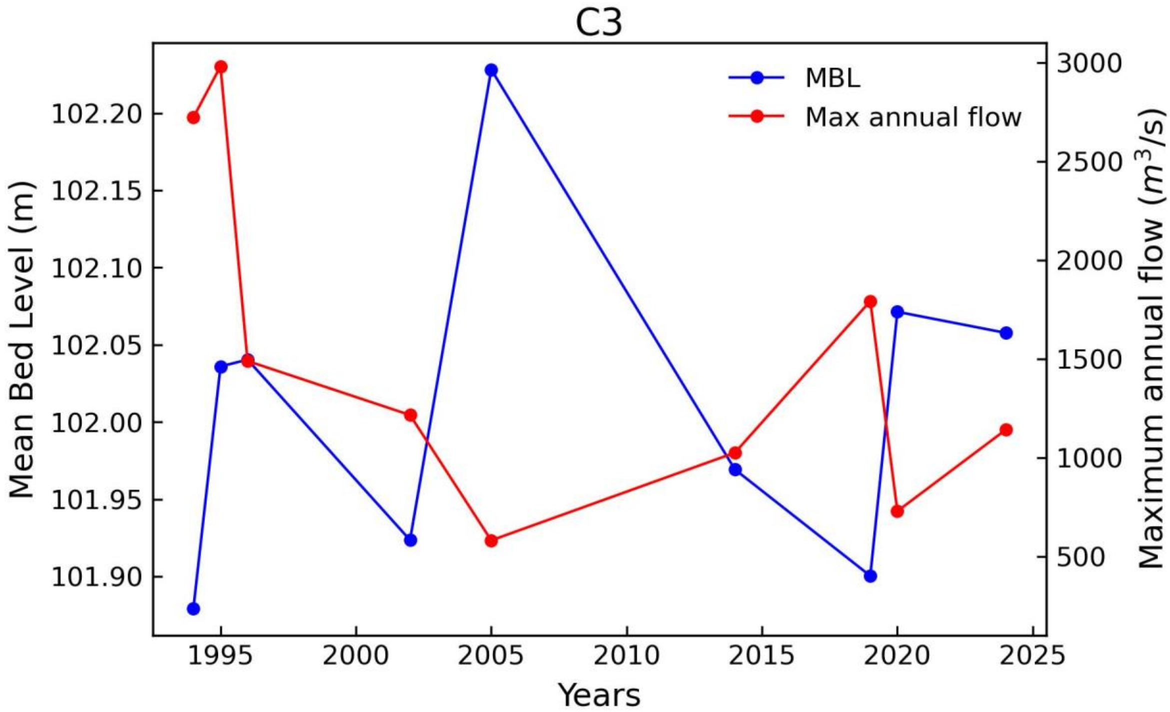

**Figure B-1: Cross-sectional profiles of C2 to C7, M11, M12, K12, and K13 for all surveyed years.**

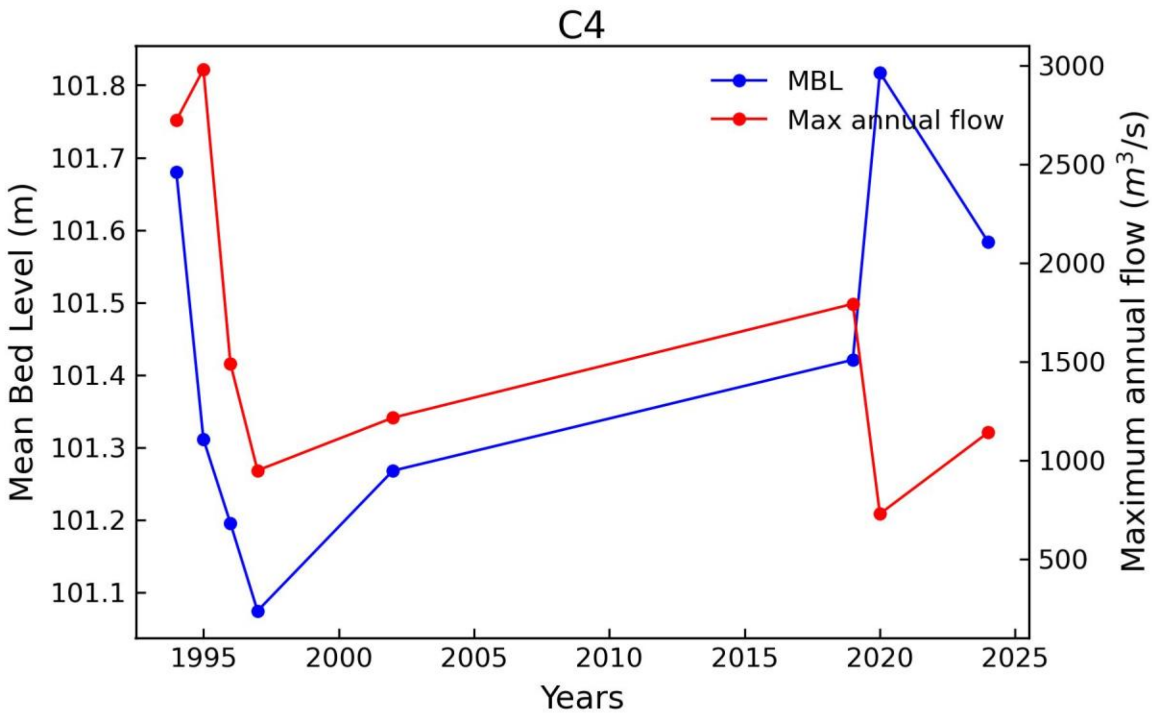
# Appendix C Maximum annual flow and mean annual flow vs. mean bed level for different survey years at each cross section

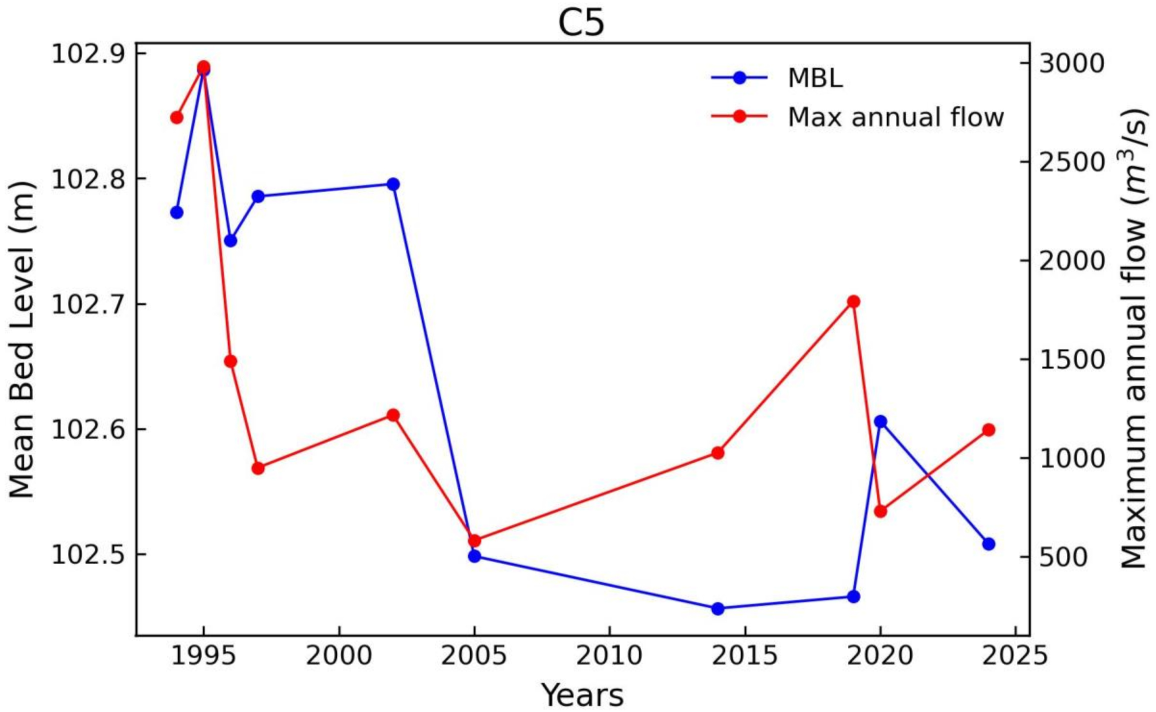
Note that axis scales differ on the plots.

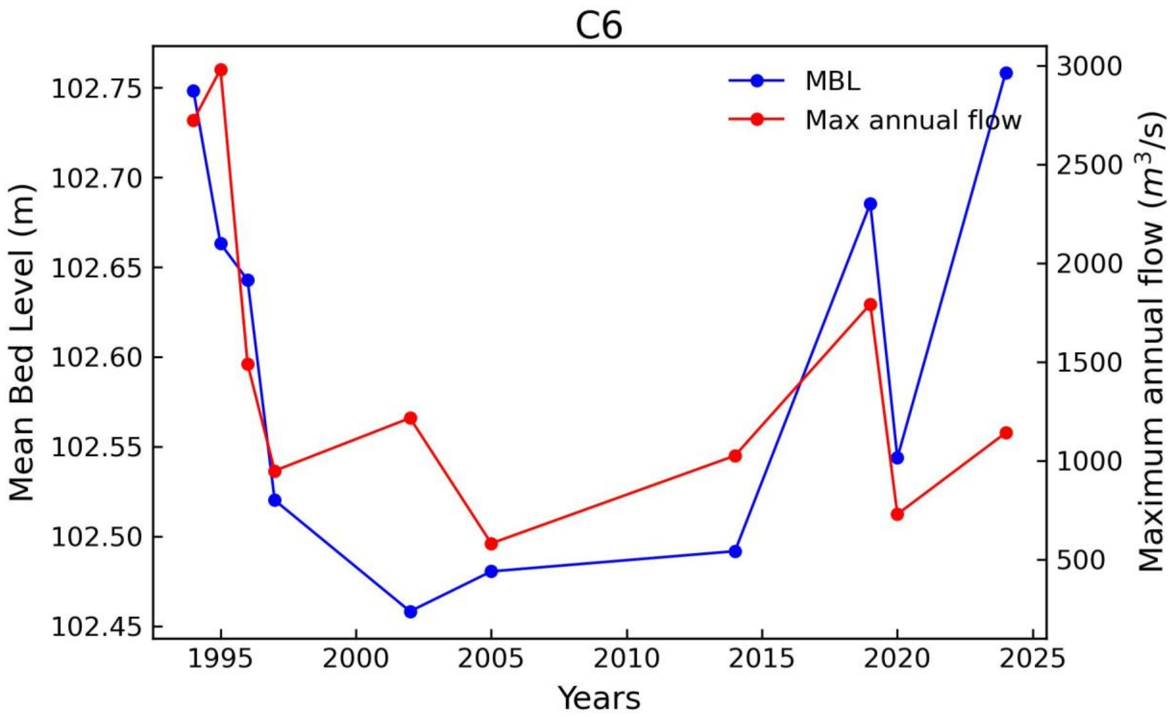


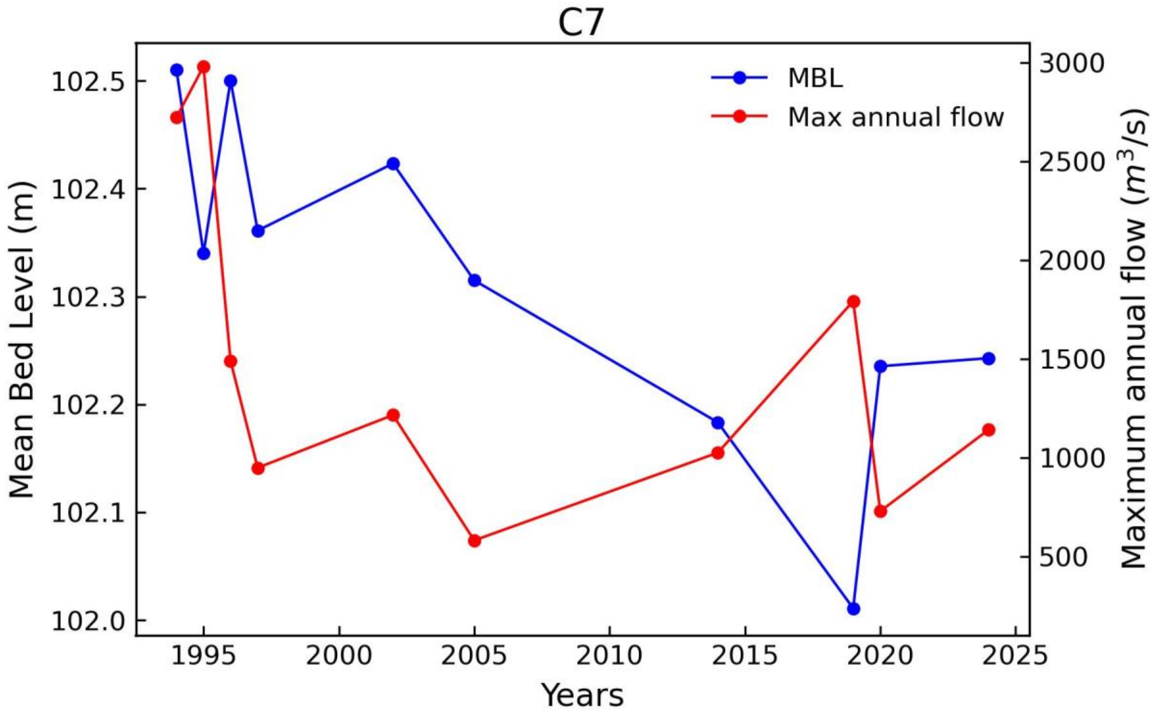



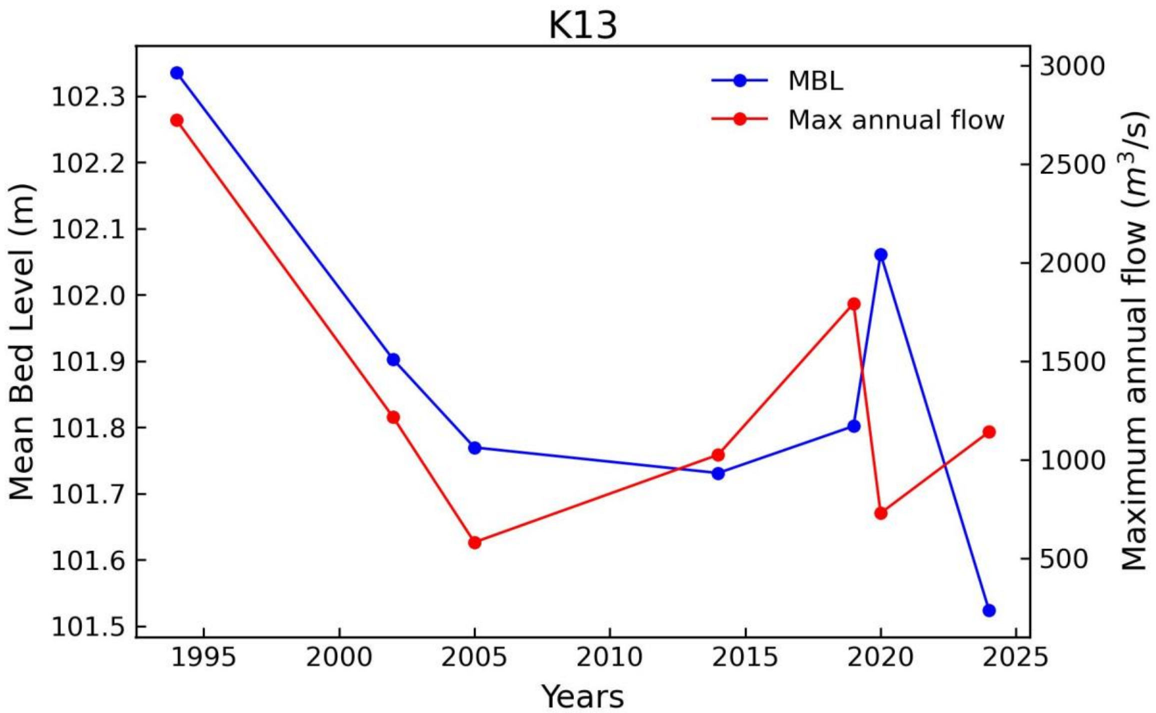

C3
MBL
Max annual flow
Mean Bed Level (m)
Maximum annual flow ($m^3/s$)
Years
102.20
102.15
102.10
102.05
102.00
101.95
101.90
3000
2500
2000
1500
1000
500
1995
2000
2005
2010
2015
2020
2025

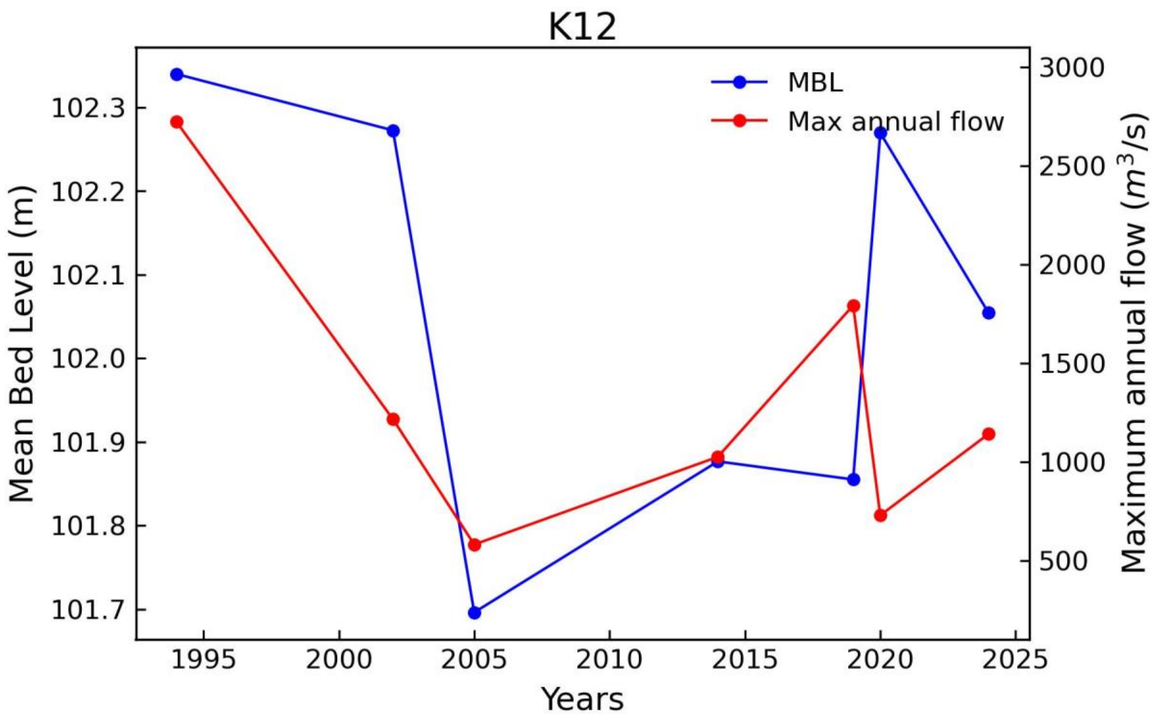

C4
MBL
Max annual flow
Mean Bed Level (m)
Maximum annual flow ($m^3/s$)
Years
101.8
101.7
101.6
101.5
101.4
101.3
101.2
101.1
3000
2500
2000
1500
1000
500
1995
2000
2005
2010
2015
2020
2025

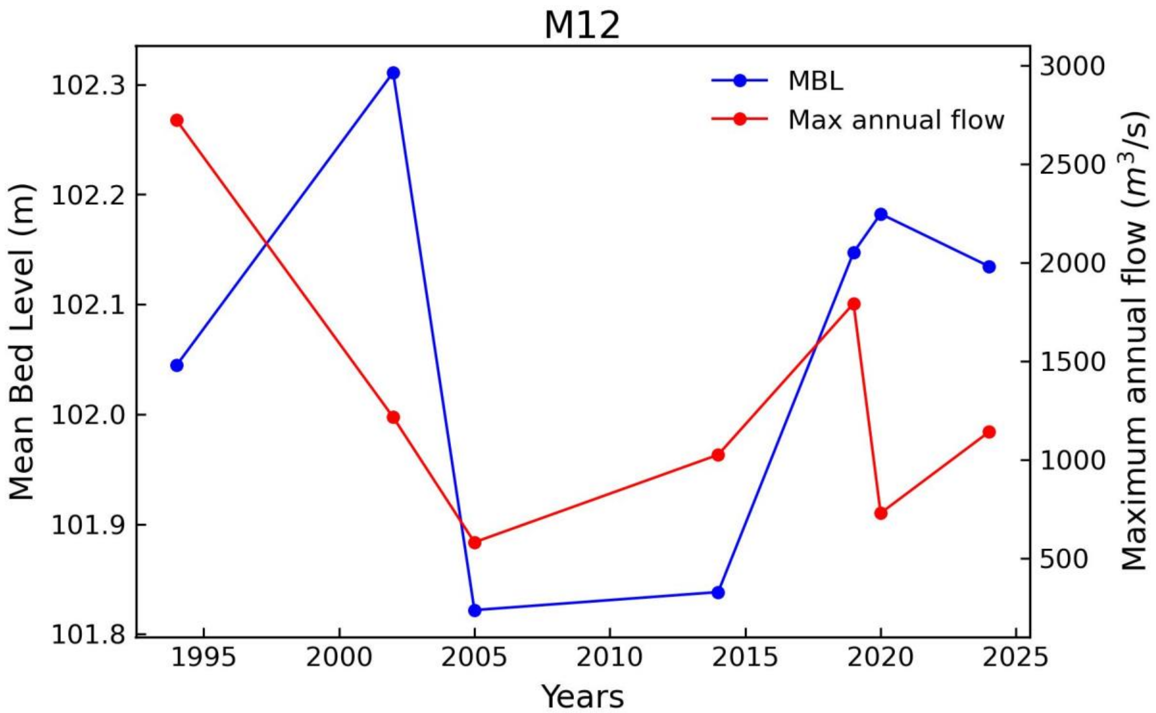

C5
102.9
102.8
102.7
102.6
102.5
Mean Bed Level (m)
3000
2500
2000
1500
1000
500
Maximum annual flow ($m^3/s$)
MBL
Max annual flow
1995
2000
2005
2010
2015
2020
2025
Years

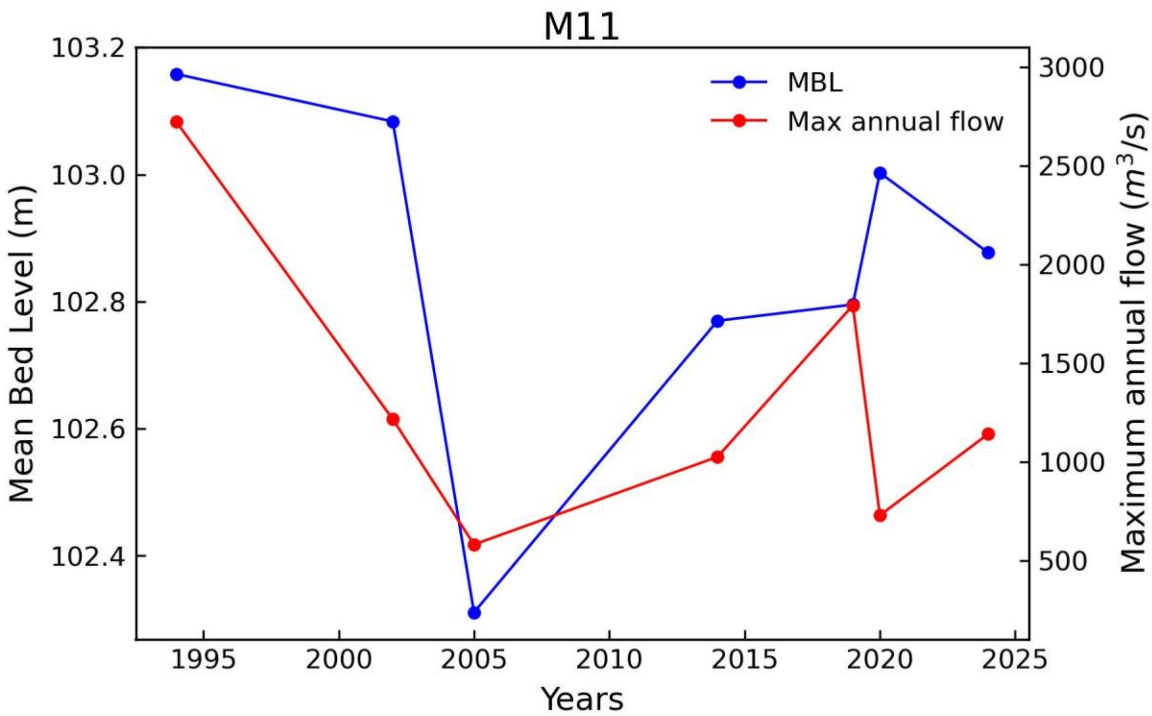

C6
102.75
102.70
102.65
102.60
102.55
102.50
102.45
Mean Bed Level (m)
3000
2500
2000
1500
1000
500
Maximum annual flow ($m^3/s$)
MBL
Max annual flow
1995
2000
2005
2010
2015
2020
2025
Years

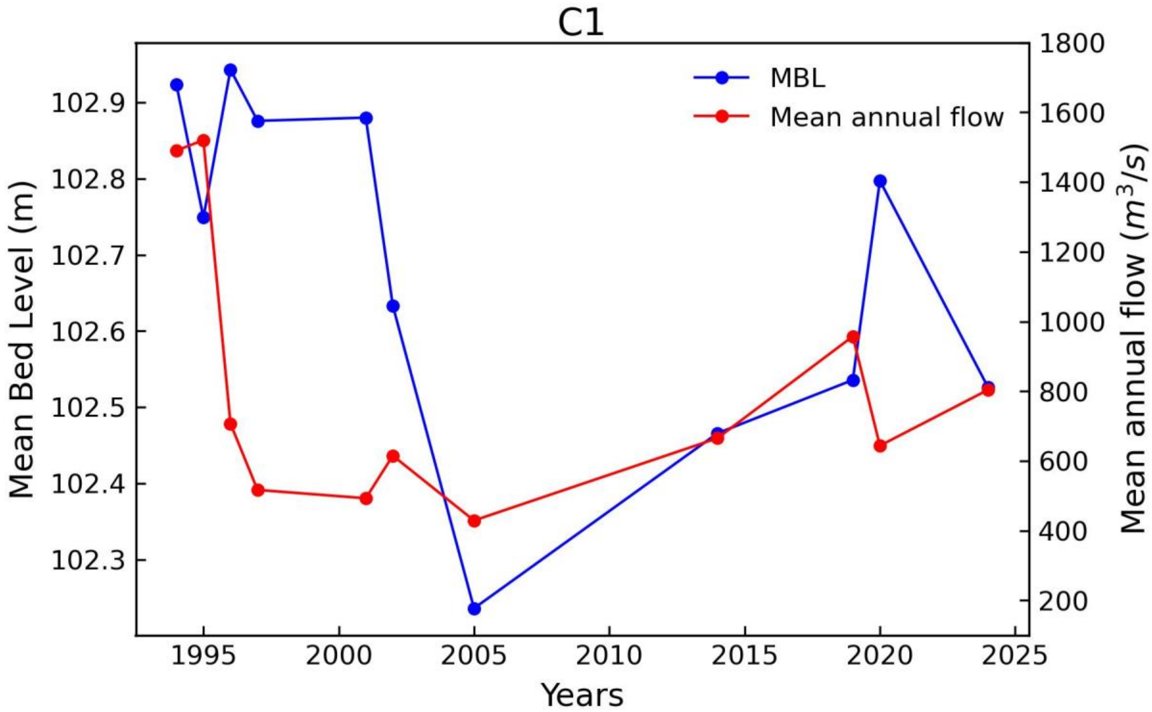

C7
MBL
Max annual flow
Mean Bed Level (m)
Maximum annual flow ($m^3/s$)
Years
102.0
102.1
102.2
102.3
102.4
102.5
500
1000
1500
2000
2500
3000
1995
2000
2005
2010
2015
2020
2025

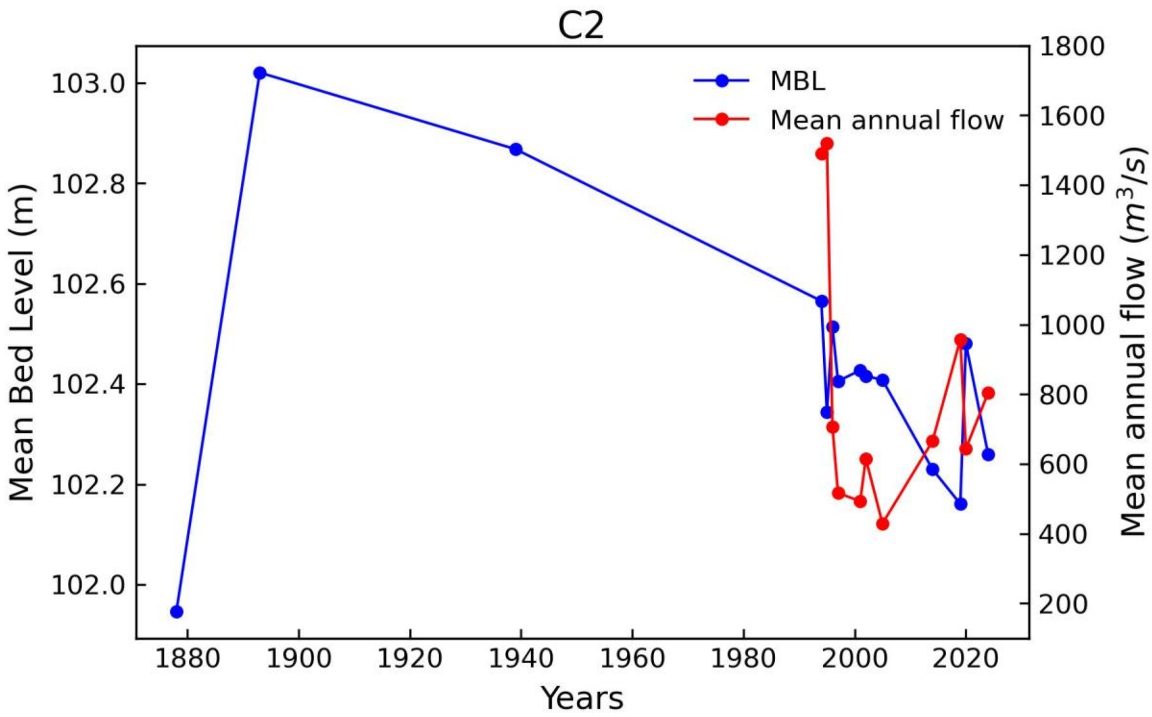

K13
MBL
Max annual flow
Mean Bed Level (m)
Maximum annual flow ($m^3/s$)
Years
101.5
101.6
101.7
101.8
101.9
102.0
102.1
102.2
102.3
500
1000
1500
2000
2500
3000
1995
2000
2005
2010
2015
2020
2025

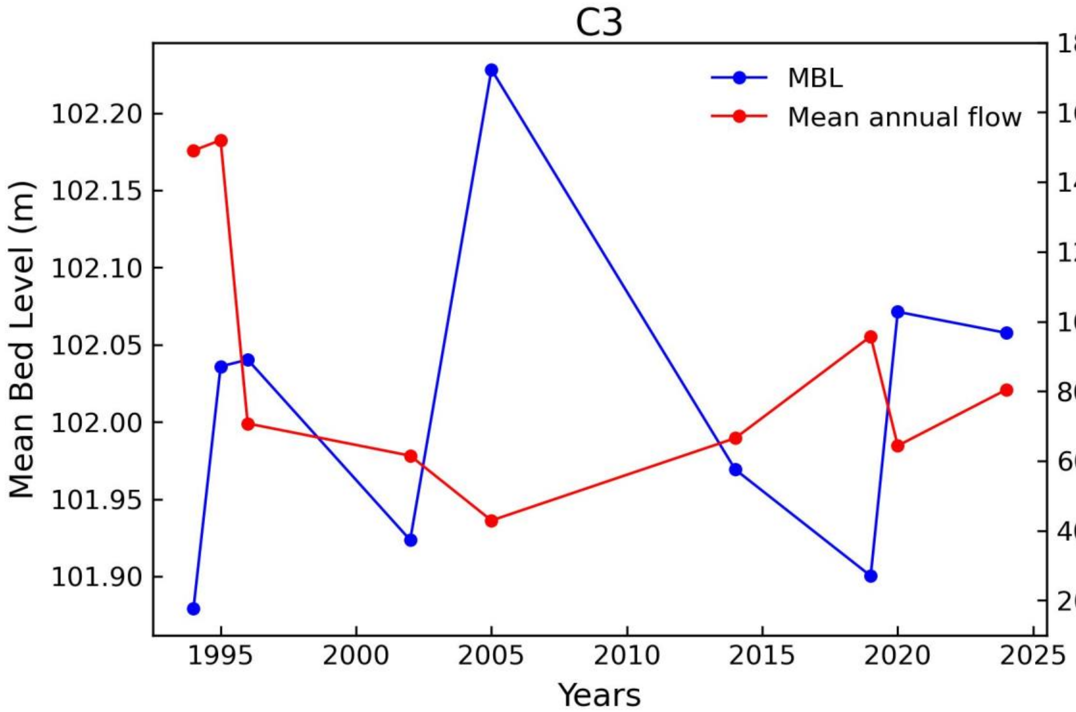

K12
MBL
Max annual flow
Mean Bed Level (m)
Maximum annual flow ($m^3/s$)
Years
102.3
102.2
102.1
102.0
101.9
101.8
101.7
3000
2500
2000
1500
1000
500
1995
2000
2005
2010
2015
2020
2025

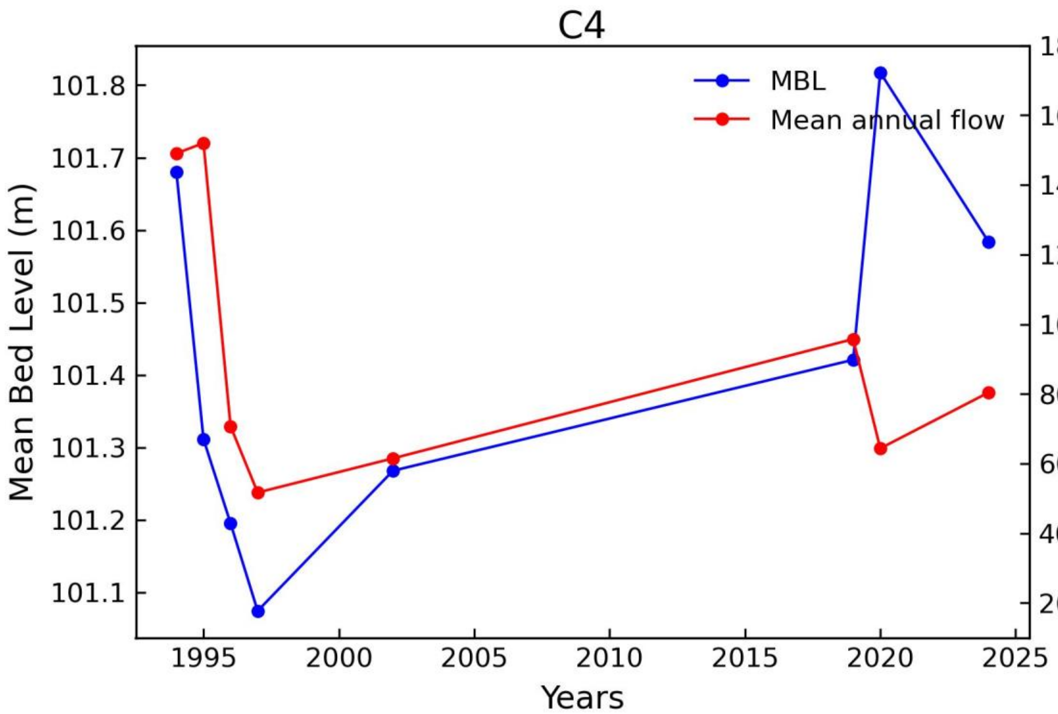

M12
MBL
Max annual flow
Mean Bed Level (m)
Maximum annual flow ($m^3/s$)
Years
102.3
102.2
102.1
102.0
101.9
101.8
3000
2500
2000
1500
1000
500
1995
2000
2005
2010
2015
2020
2025

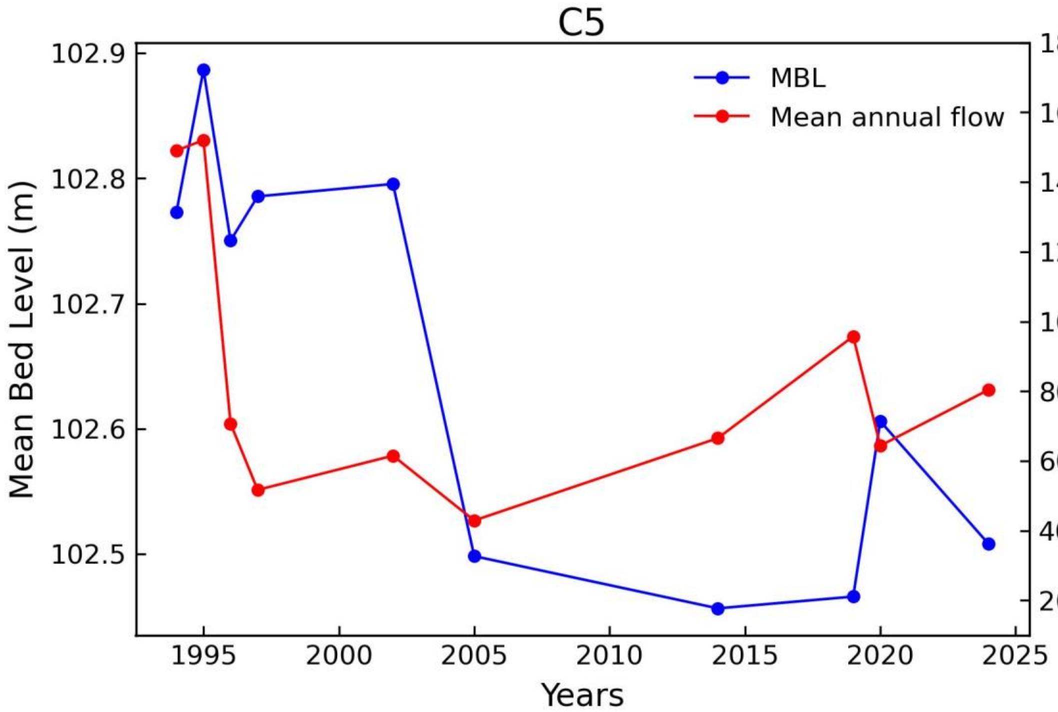

M11
103.2
103.0
102.8
102.6
102.4
Mean Bed Level (m)
3000
2500
2000
1500
1000
500
Maximum annual flow ($m^3/s$)
1995
2000
2005
2010
2015
2020
2025
Years
MBL
Max annual flow

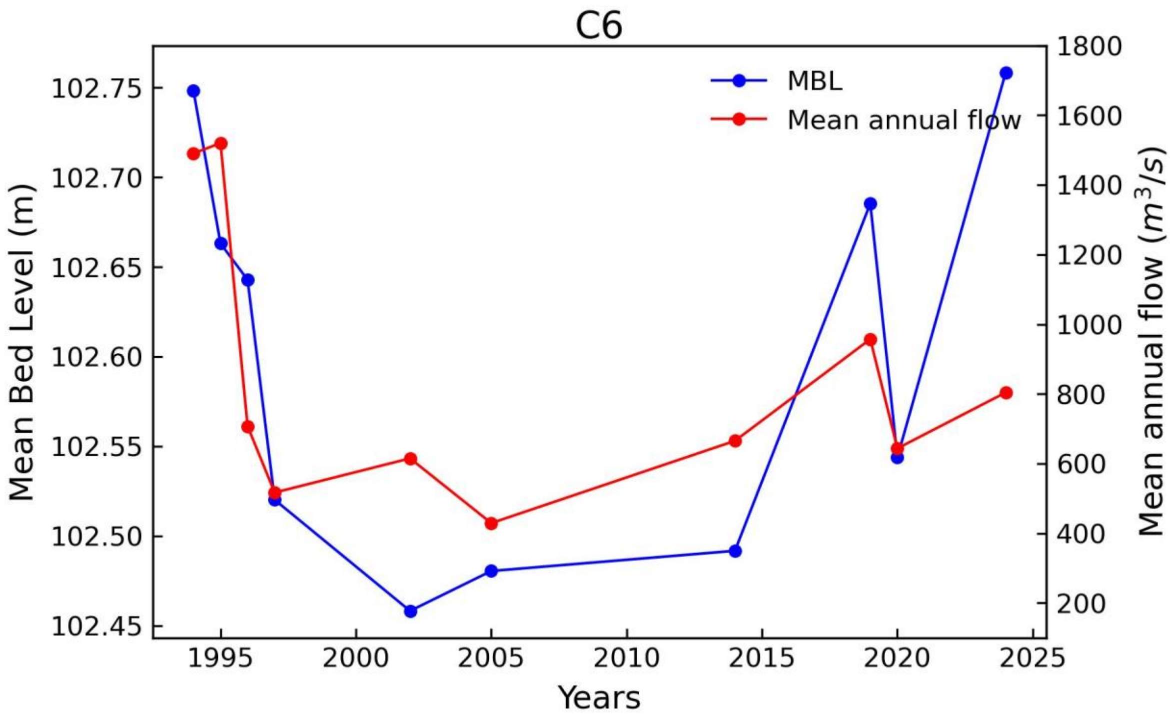

C1
MBL
Mean annual flow
Mean Bed Level (m)
Mean annual flow ($m^3/s$)
Years
102.3
102.4
102.5
102.6
102.7
102.8
102.9
200
400
600
800
1000
1200
1400
1600
1800
1995
2000
2005
2010
2015
2020
2025

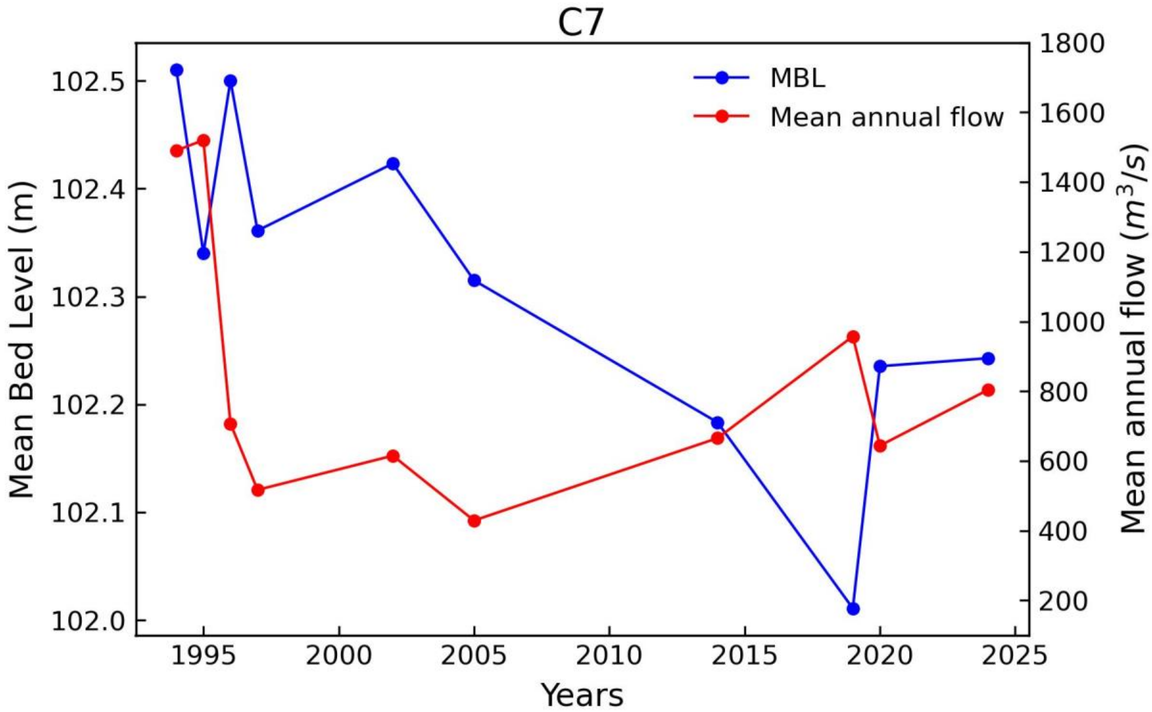

C2
MBL
Mean annual flow
Mean Bed Level (m)
Mean annual flow ($m^3/s$)
Years
102.0
102.2
102.4
102.6
102.8
103.0
200
400
600
800
1000
1200
1400
1600
1800
1880
1900
1920
1940
1960
1980
2000
2020

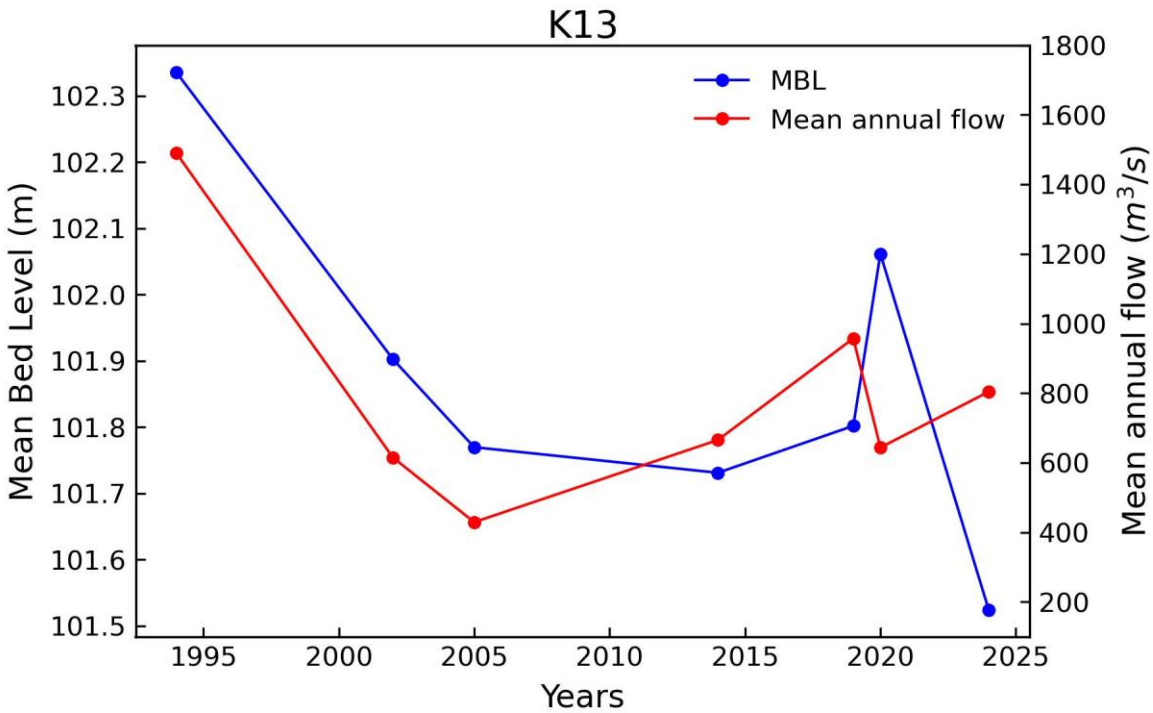

C3
MBL
Mean annual flow
Mean Bed Level (m)
Mean annual flow ($m^3/s$)
Years
102.20
102.15
102.10
102.05
102.00
101.95
101.90
1800
1600
1400
1200
1000
800
600
400
200
1995
2000
2005
2010
2015
2020
2025

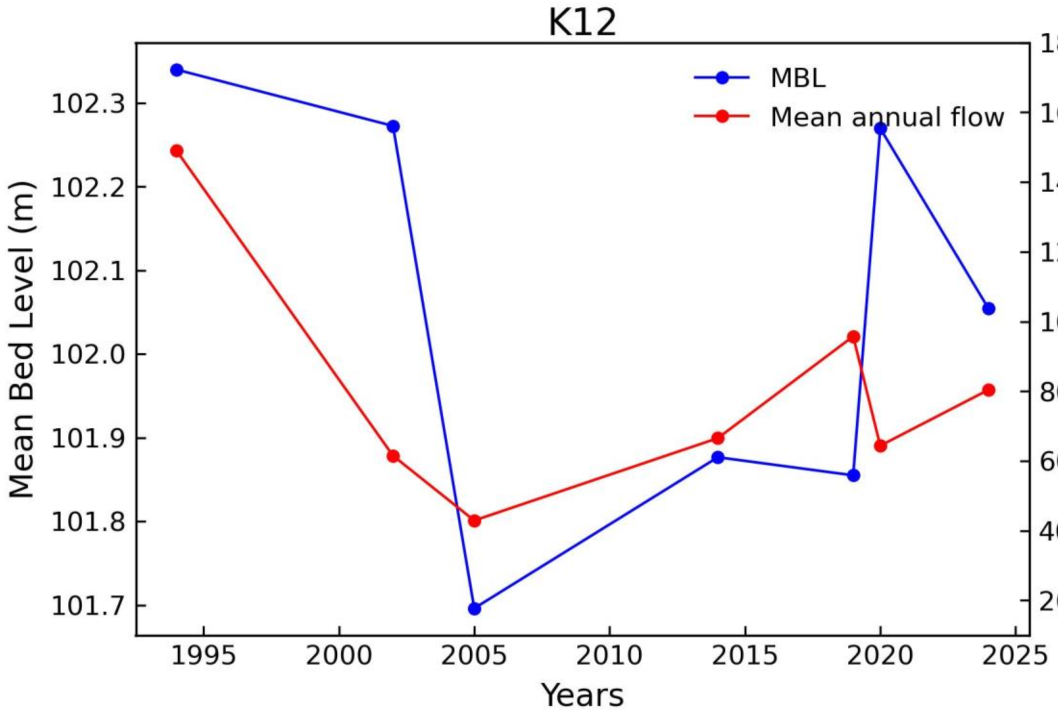

C4
MBL
Mean annual flow
Mean Bed Level (m)
Mean annual flow ($m^3/s$)
Years
101.8
101.7
101.6
101.5
101.4
101.3
101.2
101.1
1800
1600
1400
1200
1000
800
600
400
200
1995
2000
2005
2010
2015
2020
2025

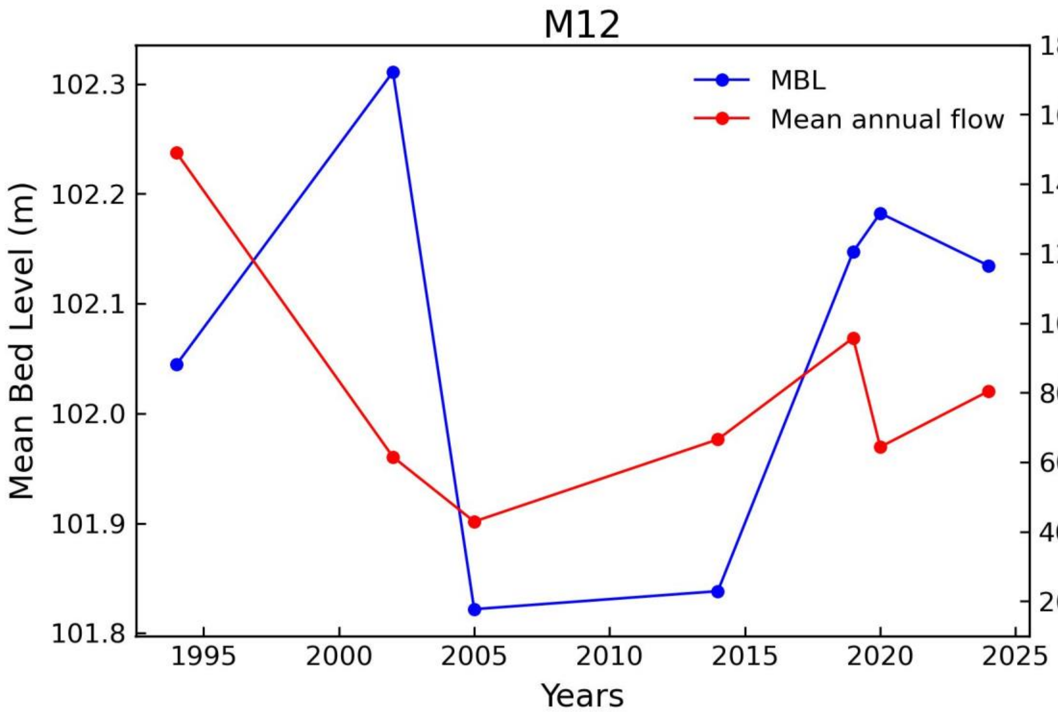

C5
MBL
Mean annual flow
Mean Bed Level (m)
Mean annual flow ($m^3/s$)
Years
102.9
102.8
102.7
102.6
102.5
1800
1600
1400
1200
1000
800
600
400
200
1995
2000
2005
2010
2015
2020
2025

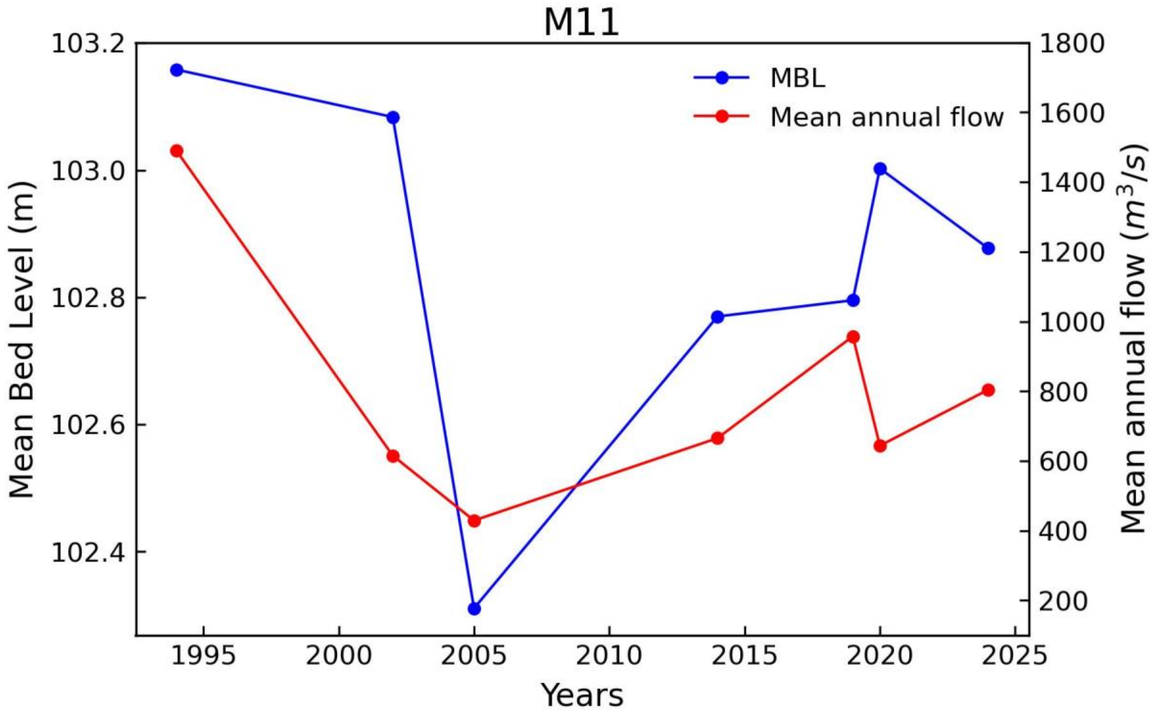

C6
MBL
Mean annual flow
Mean Bed Level (m)
Mean annual flow ($m^3/s$)
Years
102.75
102.70
102.65
102.60
102.55
102.50
102.45
1800
1600
1400
1200
1000
800
600
400
200
1995
2000
2005
2010
2015
2020
2025


C7
MBL
Mean annual flow
Mean Bed Level (m)
Mean annual flow ($m^3/s$)
Years
102.0
102.1
102.2
102.3
102.4
102.5
200
400
600
800
1000
1200
1400
1600
1800
1995
2000
2005
2010
2015
2020
2025


K13
MBL
Mean annual flow
Mean Bed Level (m)
Mean annual flow ($m^3/s$)
Years
101.5
101.6
101.7
101.8
101.9
102.0
102.1
102.2
102.3
200
400
600
800
1000
1200
1400
1600
1800
1995
2000
2005
2010
2015
2020
2025


K12
MBL
Mean annual flow
Mean Bed Level (m)
Mean annual flow ($m^3/s$)
Years
102.3
102.2
102.1
102.0
101.9
101.8
101.7
1800
1600
1400
1200
1000
800
600
400
200
1995
2000
2005
2010
2015
2020
2025


M12
MBL
Mean annual flow
Mean Bed Level (m)
Mean annual flow ($m^3/s$)
Years
102.3
102.2
102.1
102.0
101.9
101.8
1800
1600
1400
1200
1000
800
600
400
200
1995
2000
2005
2010
2015
2020
2025


M11
103.2
103.0
102.8
102.6
102.4
Mean Bed Level (m)
1800
1600
1400
1200
1000
800
600
400
200
Mean annual flow ($m^3/s$)
MBL
Mean annual flow
1995
2000
2005
2010
2015
2020
2025
Years

# Appendix D Satellite imageries of the Clutha River at Balclutha between 2016 and 2025


12-Jan-2018
Mean daily flow = 274 m³/s
N
0 0.2 0.4 0.8
Km


23-Apr-2020
Mean daily flow = 440 m3/s
N
0 0.2 0.4 0.8
Km


N
0 0.2 0.4 0.8
Km
22-Mar-2022
Mean daily flow = 267 m3/s


27-Feb-2023
Mean daily flow = 371 m3/s
N
0
0.2
0.4
0.8
Km


N
0
0.2
0.4
0.8
Km
1-Mar-2024
Mean daily flow = 424 m³/s


**Figure D-1: Satellite imagery of the Clutha River at Balclutha for seven years between 2016 and 2025.** The exact date of the satellite capture and mean daily flow values are inserted in bottom left of each image. Red lines indicate cross section locations.