CHANNEL ISLAND AND ACTIVE CHANNEL STABILITY IN THE LOWER FRASER RIVER GRAVEL REACH

by:
Darren Ham and Michael Church
Department of Geography
The University of British Columbia
Vancouver, B.C. V6T 1Z2

March 5, 2002

Executive Summary

Bar growth and island development are integral parts of the process of sediment transfer along the gravel reach of Fraser River that create and maintain aquatic and riparian habitats. This report examines channel stability -- the summary consequence of bar growth and change -- and trends of island development during the twentieth century.

Since 1913, the active channel zone has become 22% narrower overall. Trends in channel width follow trends in river flow, but are heavily damped. Furthermore, there is no net trend in flood magnitude through this period. The greatest changes in channel zone width have occurred between Agassiz and Sumas Mountain, that reach of river where aggradation rates are also greatest. The area of the active channel bed follows similar trends, of course, with the main changes occurring downstream of Agassiz, and substantially less total area in 1999 than in 1913.

In significant degree, this process has been driven by the loss of secondary channels behind channel islands. Some have silted up naturally; some have been cut off. The net result has been to incorporate mature islands (ones constructed to floodplain level, with well-developed forest cover) into the floodplain. This, in turn means that there has been a loss of mature island surface.

On the other hand, the total island area, whilst it declined in most reaches through the middle years of the century, has recovered to the point that it was not much different in 1999 than it had been in 1928. Offsetting the net loss of high island surface is a substantial increase in relatively low island surface with early-stage bush vegetation. This fact is reflected in a volumetric bias toward bank erosion over bank deposition. These low islands tend to be much more fragmentary than the old, mature islands. There are significant differences amongst sub-reaches, with a notable increase in island occurrence in reach 3, adjacent to Sumas Mountain, and also in the Gill Island-Carey Point area and in the vicinity of Spring Bar.

We present changes in channel cross-section area between 1952 and 1999, dates of detailed survey of the channel, at 400 m spacing. Cross-section changes are quantified in relation to a water level estimated to approximate bankfull level. Generally, single-channel cross-sections have increased in area during the half-century, but ones including islands have not. In general, the changes are not statistically significant, except in the Agassiz-Laidlaw reach (where the river is degrading).

We also examined the long profile of the river at three survey dates, 1952, 1984 and 1999. The channel thalweg (line of deepest flow) is the basis for this analysis. The successive profiles confirm sediment budget results, showing net degradation upstream of Agassiz and net aggradation downstream. Interestingly, a few prominent riffles are observed at each date that probably are disproportionately significant in controlling river water levels. These major riffles change through time.

In summary, there is a long-term trend for the filling of secondary channels and the consolidation of islands into a few mega-islands. At the same time, the cross-section area of the principal channel is increasing. The former trend is emphasized during periods of below average floods, and it is likely that the latter is the manner in which the river regains conveyance during major floods. the overall result is a simpler, somewhat narrower channel

than early in the century. However, substantial complexity remains and may increase in future, depending upon the further development of many recently-established, low-level “islands” along the river.

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Cover photo: South Cromarty Island (across from Island 22 boat launch) looking south towards mainland shoreline. Photo taken during 1948 flood by Mr. G. Blom, RPF, former Chief Forester, Scott Paper Ltd. Photo courtesy of Scott Paper Ltd., New Westminster, British Columbia.

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1.0 INTRODUCTION

Between Mission and Laidlaw, Fraser River has formed a wandering channel on a confined, gravel alluvial[1] fan. This type of river is characterized by an irregularly sinuous channel, frequent large wooded islands, and low-order braiding (Desloges and Church, 1989; see Figure 1). These rivers commonly have an extensive network of perennial, seasonal and abandoned backchannels within the adjacent floodplain. The backchannels indicate locations where the main channel once flowed and are subject to reoccupation, especially during large floods. Channel morphology in these rivers is dominated by the erosion, transport and deposition of the coarser sediments. These sediments are deposited and stored locally within the channel. Since the water must flow around the deposited sediments, the current attacks and erodes adjacent banks to make room for the flow. The result is that the river is laterally unstable. Bank erosion, as well as flooding, presents considerable risks to the people and infrastructure located along the floodplain of lower Fraser River. For roughly a century now, efforts have been continuing to protect developed areas through a system of dykes and through bank ‘hardening’ – protection with placed rock.

It has been demonstrated that as a consequence of these programs (which include rail and highway construction – refer to Figure 1), a large percentage of the outer channel banks has been constrained from further lateral movement (Church *et al*., 2001). This bank hardening may be related to a narrowing of the active channel zone (Church *et al*., 2001). Should this trend continue, there are two possible consequences. The first is that since channel confinement creates deeper, faster flows, bed material may be transported further downstream, creating new sites of aggradation and lateral instability. Second, the river may be forced from a wandering to a single-thread pattern (Church *et al*., 2001) as has been demonstrated along several European Rivers (Braga and Gervasoni, 1989; Decamps *et al*.,1989; Steiger *et al*., 2001).

Large islands are formed where bars build to sufficient height vertically that fine sediments accumulate on the tops as floodwaters recede and a number of pioneering tree species (especially black cottonwood and willow; Boniface, 1985) become established. This vegetation is able to trap further accumulations of fines, allowing vegetation to mature and thereby provides some measure of bar stability, hence island growth.

Channel confinement therefore has implications for the occurrence and stability of channel islands. Increased flow depth and velocity are likely to interfere with island development by reducing the volume of deposited fines or stripping away existing deposits. Boniface (1985) points out that increased flood duration, as may occur within a confined channel zone, may prohibit vegetation establishment by eroding or burying seeds, while conditions of prolonged inundation can inhibit seed germination. Island establishment may also have been impacted in recent decades by the reduction of large woody debris along the channel as the result of operating the debris trap near Hope. Wood stranded or partly buried on bar heads traps fine sand on the lee side, and has been identified as a

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[1] Alluvial indicates processes or sediments associated with a river. Hence ‘alluvial sediments’ are deposits of the river.

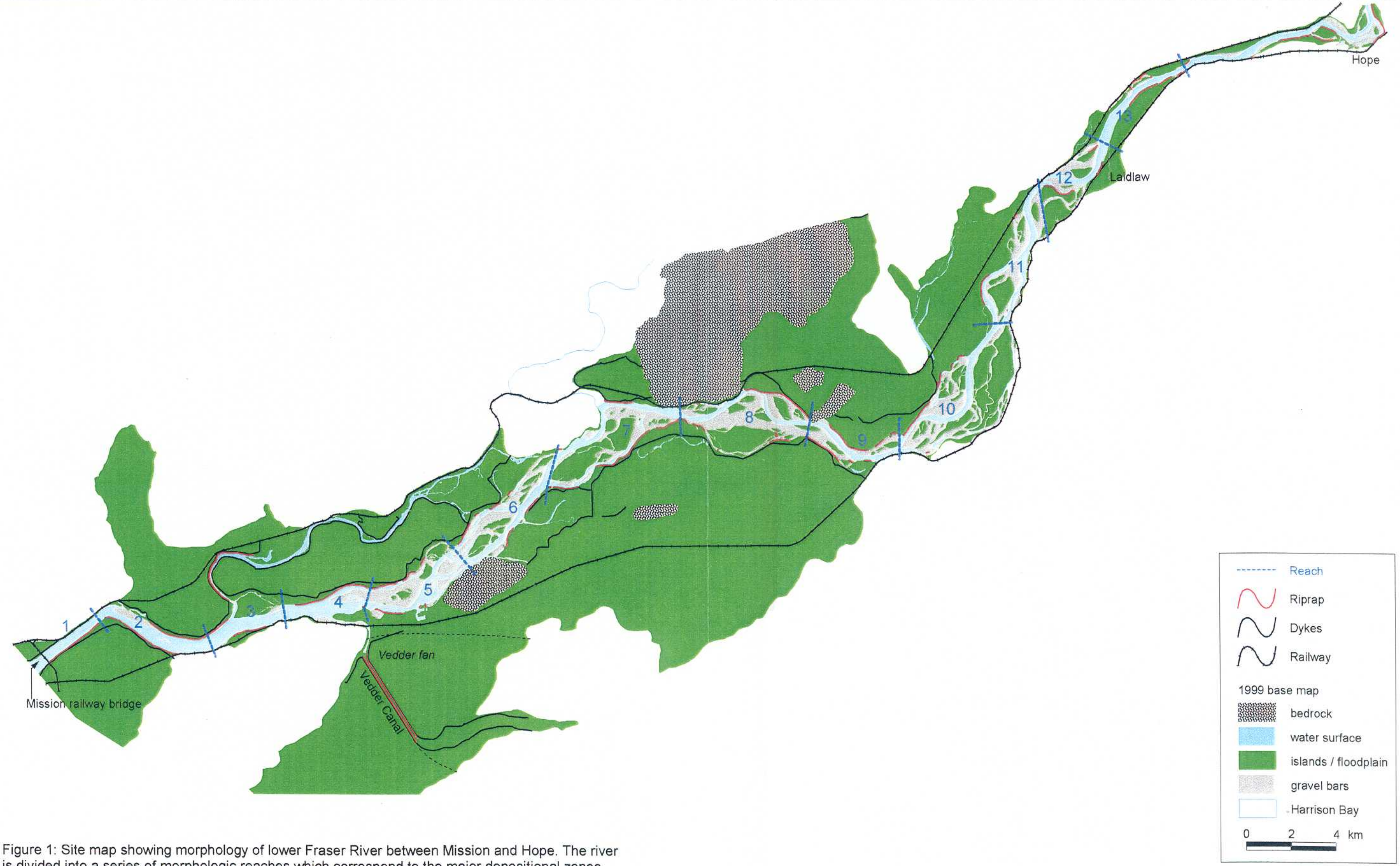

Figure 1: Site map showing morphology of lower Fraser River between Mission and Hope. The river is divided into a series of morphologic reaches which correspond to the major depositional zones and narrower, stable transport zones (where little sediment is deposited) within the gravel alluvial fan.

nucleus for subsequent bar growth (Hickin, 1984). This process creates favorable conditions for the establishment of riparian vegetation (Kellerhals *et al*., 1976). Even where seedlings do establish, channelization results in sediment becoming mobilized more quickly from existing channel bars (Church *et al*., 2001). The accelerated turnover rate of bar-stored sediments discourages firmly rooted vegetation from developing and stabilizing the bar surface.

The larger islands along the reach, established in areas of formerly active channel change, appear to develop by sedimentation of inter-island channels and amalgamation of several earlier formed islands. This process has occurred over the past forty years near the mouth of Harrison River, where a large island has developed between Minto Channel and the main river (Church and Weatherley, 1998). Islands might also form from avulsion[2] into the floodplain. Bank protection limits the possibility for avulsion along much of the reach. In addition, bank protection reduces the possibility for the river to move laterally into the adjacent floodplain. As a result, the remaining unprotected islands might increasingly be eroded away as the river creates flood conveyance room within the confined channel.

Why is this important? There are several major reasons. Some of the islands are Indian Reserves, so preserving this land base is important because of its traditional value. As well, a number of islands have cottonwood plantations and are commercially logged, so there are economic values to consider. Finally, islands are a significant part of a diverse riverine ecosystem. The natural ecosystem of lower Fraser River has already been negatively impacted over the past century by clearing much of the original riparian forest, draining and filling of wetlands and isolating side- and backchannels by dyking (Church *et al*., 2001). Existing channel islands, therefore, remain an important source of nutrients, and play an important role in maintaining overall habitat diversity. From a river management perspective, it is therefore important to quantify changes in island morphology over recent decades to inform future management strategies.

2.0 LATERAL CHANNEL STABILITY

Bank erosion and deposition are natural, on-going processes in wandering channels that occur in response to sediment exchange through the system. Active channel zone widening occurs naturally during extended periods of above-average flood discharges because of bank erosion and vegetation stripping. Active channel width is defined as the average width of water and exposed bar surfaces between established edges of perennial, terrestrial vegetation (see Figure 2). Conversely, channel narrowing occurs during periods of below-average flood flows, as vegetation becomes established or matures on elevated bar surfaces along the channel. Historic trends in channel zone width between the outer banks are given in Figure 3a. Channel width largely follows the trends in flows over time, though they appear to be quite strongly damped in comparison with flow trends. This may in part be due to inertia in the sedimentary system, but it certainly also is affected by the timing and dates of the width

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[2] Avulsion: sudden re-routing of the channel into a new course when the river breaks its bank during flood.

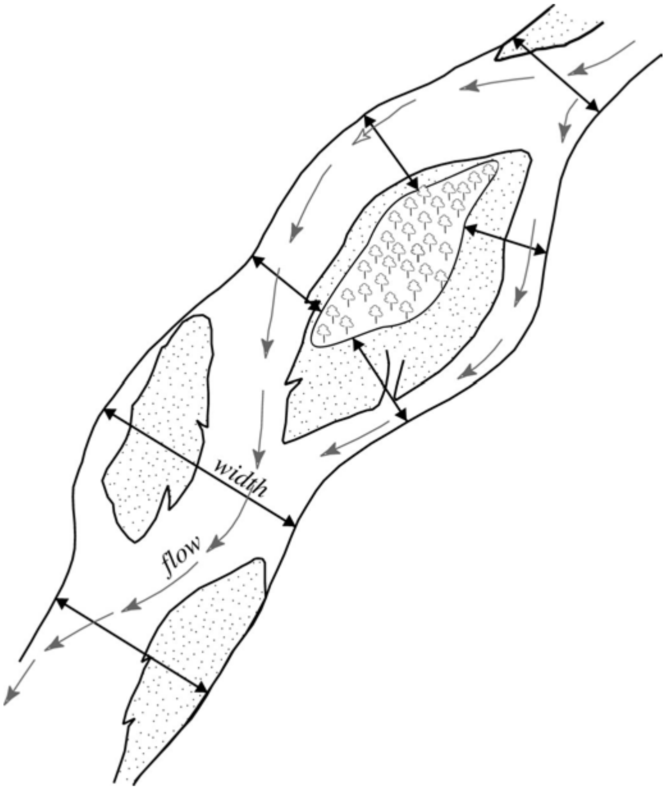

Figure 2. Definition sketch for active channel width calculation. Width is measured between the outer channel banks across the surface of water and exposed gravel bars, but does not include the channel islands. Average width is calculated in the GIS by summing the *area* of water and gravel bars, then dividing by the length of the main flow path.

observations. However, channel width did not increase much between 1949 and 1971 despite the sustained period of above average flows, whilst channel narrowing appears to have accelerated since 1971. These appearances may be due, in part, to bank hardening along the river. However, it is difficult to isolate this impact from natural variations. Overall, the river is 22% narrower than in 1913 and narrowing has occurred along most channel reaches between Mission and Laidlaw (Figure 3b). This narrowing also represents a loss in the area of potential habitat substrate for fish and aquatic insects (Figure 3c).

In comparison with the outer banks along the active channel zone, islands within the river are largely unprotected (the main exception is Peters Island). Therefore, major adjustments in channel width should occur mainly as a result of changes in the area of channel islands. Figure 4(a and b) illustrate these changes over time, as measured from sequential aerial photographs. In general, island area declined along most reaches between 1928 and 1949, superficially suggesting that the active channel zone was widening. The decrease may be partly explained by erosion during the large flood of 1948[3].

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[3] The reader should recognize that our information of channel zone width and island area is restricted to map dates (as shown in figure 3a), which do not necessarily correspond with the timing of trend-setting changes in the river, so temporal resolution is somewhat limited.

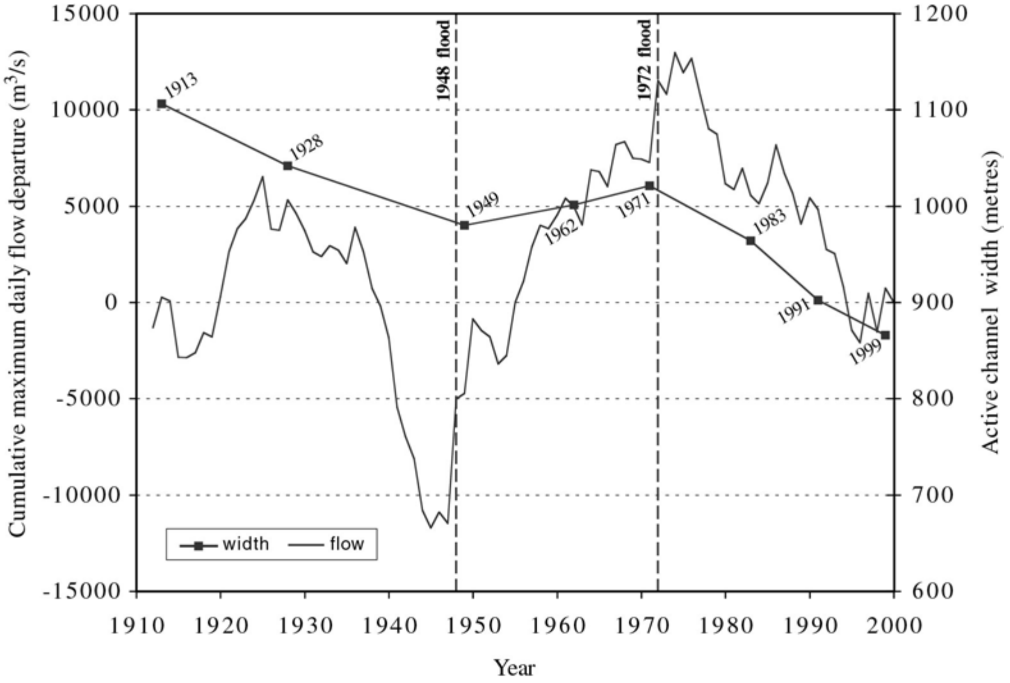

Figure 3 (a). Variation of active channel zone width between the outer banks for various dates since 1913 in relation to trends of annual maximum daily flow. The flow trend is indicated by the cumulative departure from the long-term mean annual flood. A descending plot indicates consistently below-average flows, an ascending plot indicates consistently above-average flows, and a horizontal plot indicates flows near the long-term average. Cumulative departures reveal trends in flow regime much more clearly than the flow data themselves. Modified from figure 24 in Church et al., 2001.

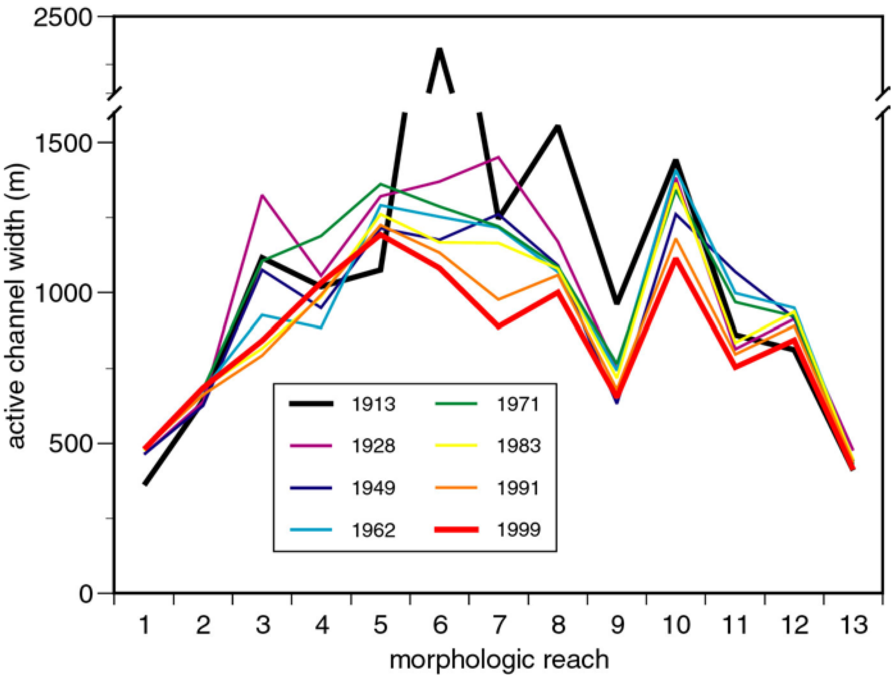

Figure 3 (b). Active channel zone width over time along individual channel reaches. The 1913 and 1999 dates are emphasized to illustrate the decrease in width along most reaches. Reach locations are given in Figure 1.

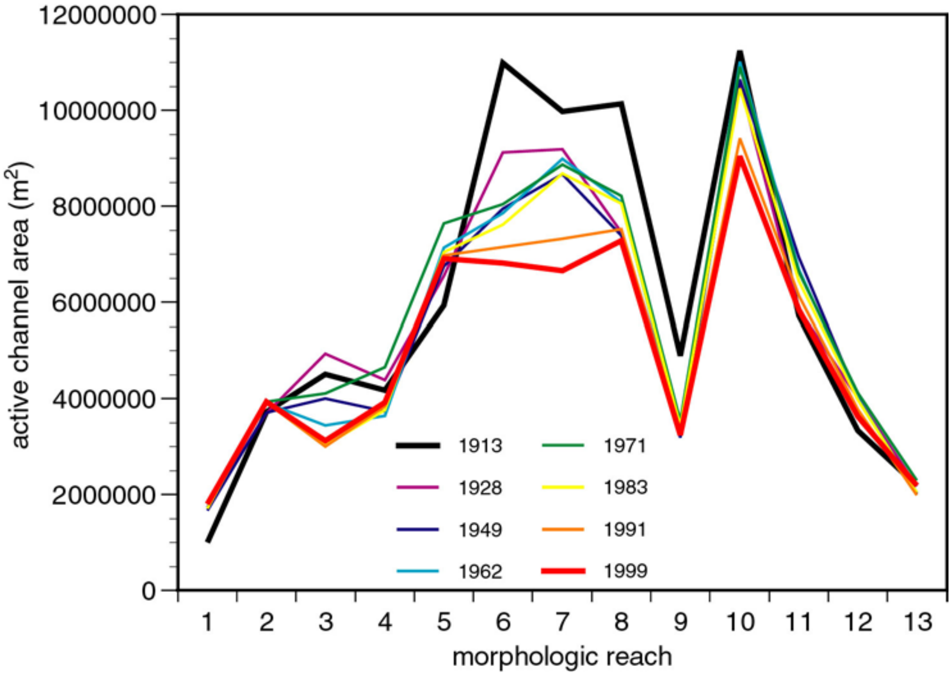

Figure 3 (c). Active channel zone area over time along individual channel reaches. The 1913 and 1999 dates are, again, emphasized to illustrate the decrease in area over time along most reaches. The trends vary slightly from figure 3b because of differences in reach lengths (see Figure 1).

However, since the active channel zone actually narrowed, island erosion must have been countered by an even larger amount of bank reconstruction. In fact, many islands identified on the 1928 photographs were coded as floodplain polygons (i.e. were outside the active channel zone) on the 1949 mapping. They had been isolated from the active channel zone by dyking, flood gate construction and siltation. The corresponding loss of backchannels around these islands is the primary cause of channel narrowing, hence the loss of area. The loss of island area continued to 1971 (in fact, mainly in the decade 1960-1970) but they have generally increased in size since, which is consistent with the dominantly below-average flood flows and declining overall active channel zone width. Indeed, the present total surface area of islands is actually equal to the 1928 totals, and is greater than in any other year since the 1948 flood, when the dyking program was expanded.

Observed changes in island area are not dramatic, since changes occur relatively slowly along the river with sites of persistent erosion and deposition lasting for years to decades. That the river is not highly unstable reflects the modest transport rate of bed sediment compared to the large size of the channel.

It follows from the preceding arguments that bank erosion and deposition should similarly conform to trends in the long-term flows (see Figure 5). Lateral bank deposition rates exceeded bank erosion rates from 1928 to 1949 and since 1983, which is consistent with observed channel narowing during these periods of mostly below-average flows. Similarly, bank erosion rates were greater than deposition rates between 1949 and 1971 when channel width increased and flows were mostly above-average. However, the increase in width from 1949 to 1962 is surprisingly modest given the disparate 19:1 ratio

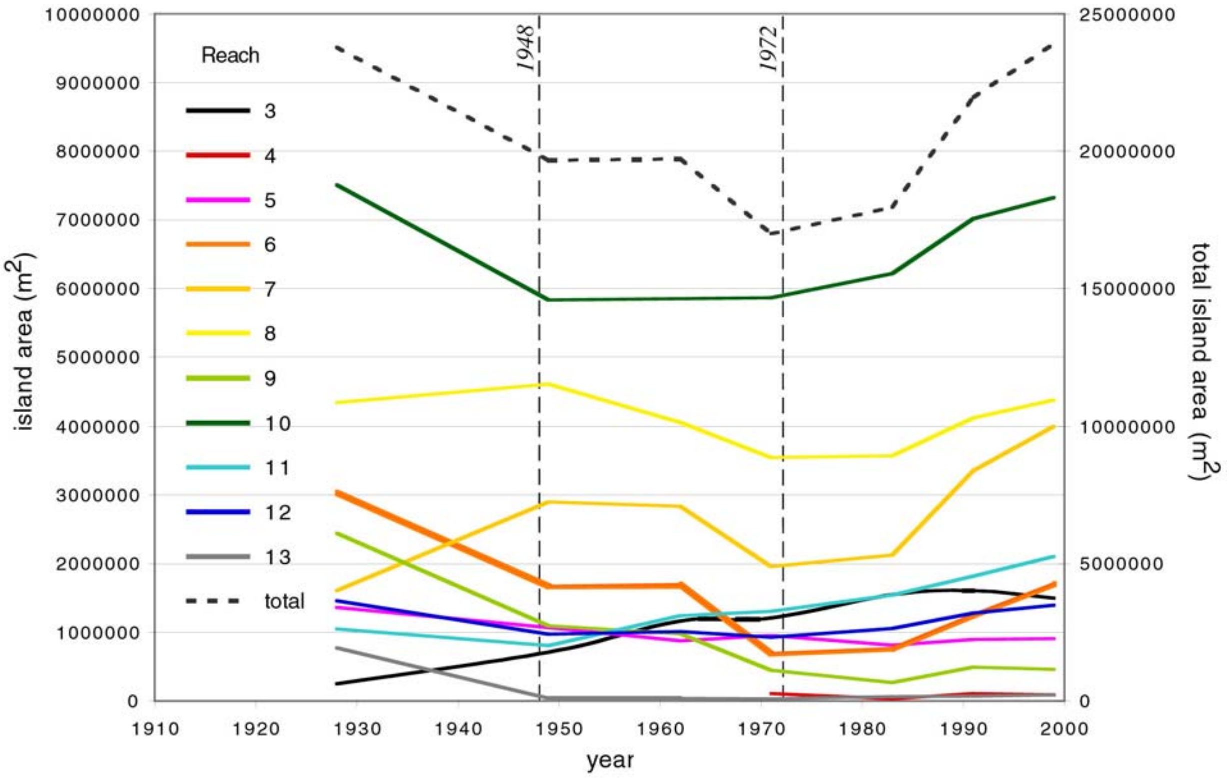

Figure 4 (a). Temporal changes in island area along lower Fraser River. There are no islands in reaches 1 and 2 in any period, nor any islands in reach 4 before 1971.

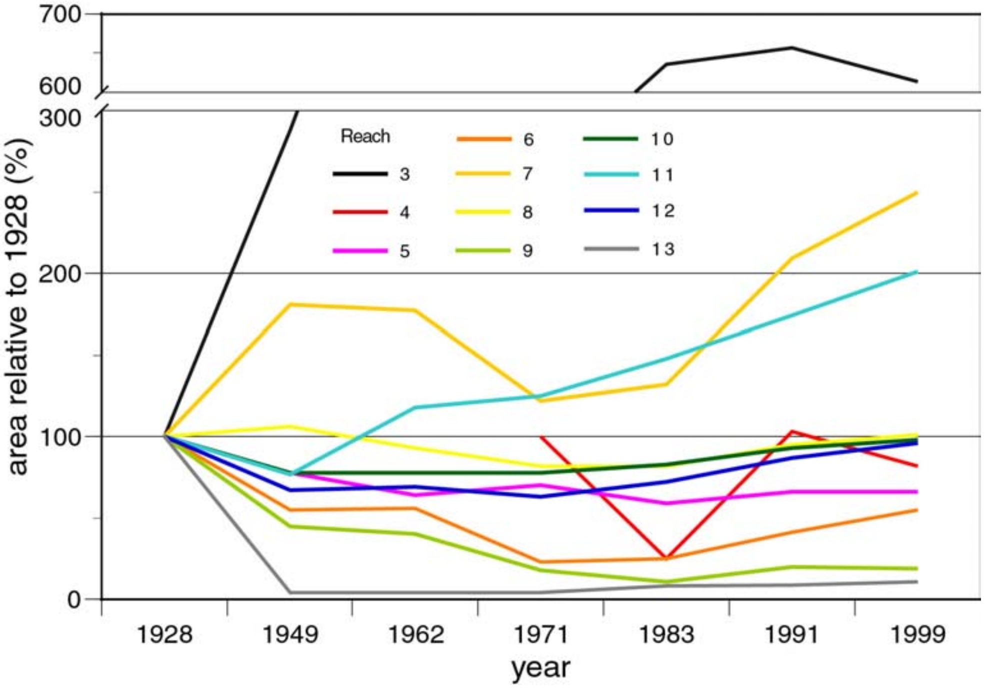

Figure 4 (b). Area of islands expressed as a percentage of area in 1928.

favouring bank erosion. The remaining period, 1971-83, displays an anomalous pattern – that is, there was more bank erosion than deposition even though channel width decreased. This may be due to vegetation growth on gravel bars – although there was a very large flood in 1972, flood flows were generally below average during this period. The processes of vegetation growth on gravel bars and stripping of vegetation on bars by erosive flood flows occur independently of bank erosion and deposition and therefore partly obscure relations with channel flow and width.

In comparison to lateral trends, volumetric trends in bank erosion and deposition demonstrate a consistent erosional bias, that is, the erosional volume exceeds the depositional volume in all periods (Figure 6a).Volumetric measurements derive from the sediment budget of the river (see Church *et al.*, 2001). This bias is calculated as 2.5:1 in 1952-99 (Mission to Agassiz), and 2.5:1 in 1952-99 from Mission to Laidlaw. Again, these results suggest that the river should be widening through loss of island and floodplain sediments, but the opposite circumstance has been observed. The erosion of well-established (mature) island and floodplain deposits produces the bias since these areas were higher (i.e. represented a thicker body of sediment) than sites of recent island deposition or growth because of vertical aggradation. There is direct evidence to support this claim: if overbank sediments are removed from the calculations, bank erosion and deposition volumes nearly balance between 1952 and 1999 (Figure 6b). This implies that while island area is being maintained along the channel, mature riparian forests are being lost and increasingly replaced with younger vegetation. If true, then the shape of the channel may be adapting to accommodate these changes. This proposal will be investigated in the following section of the report.

Figure 5. Bank erosion and deposition for different periods (expressed as annual changes). Bank erosion is defined as areas mapped as islands or floodplain on the earlier date and water or partly submerged gravel bars on the later date (the situation is exactly reversed for deposition). Erosion and deposition rates are unaffected by changes in water levels between mapping periods because vegetated areas are exposed at all flows below flood.

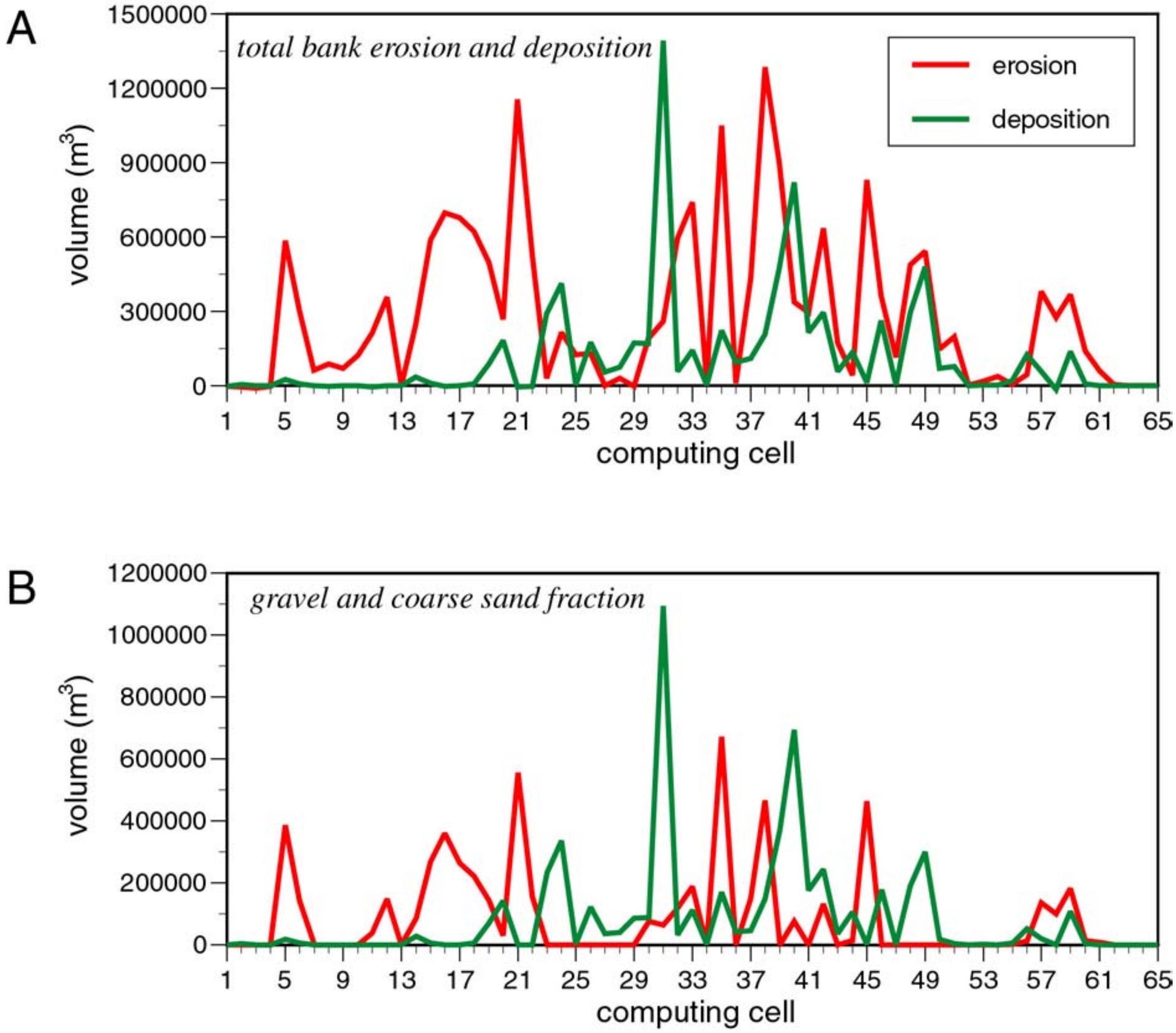

Figure 6. Bank erosion and deposition for individual 1-km computing cells. Volume changes are calculated by (A) direct difference of survey, including gravel, sand and overbank fine sediments and (B) direct difference of survey excluding overbank material.

3.0 CROSS-SECTION AND LONG PROFILE CHANGES

Cross-sections

In addition to adjusting its form through changes in channel width, the river may adjust its depth to maintain flow conveyance. For a given flow, a reduction in width will result in increased flow depth, since depth is more easily adjusted than velocity. Along rivers with mobile beds, depth can increase by lowering (erosion) of the channel bed or by raising water levels for any given discharge. Because the gravel reach is known to be aggradational, the latter circumstance must be occurring, although the channel may be degrading locally. Adjustments in channel shape can be determined by examining the cross-section and longitudinal profiles of the river over time.

Cross-section profiles along the river were derived from bathymetric surveys that have been completed in 1952, 1984 and 1999 (see Church *et al*., 2001 for a complete description of the surveys). Since each survey encompasses a different spatial area, the data density varies between surveys, and the transverse survey lines are rarely coincident, it was not possible to simply extract profiles for each year from the bathymetric data. This presents some difficulties, since conventional cross-section comparisons over time require that the profile lines match between surveys. In practice, this is achieved by surveying the bed and channel banks between fixed endpoints at some regular interval (commonly every bankfull width) along the channel. In order to overcome the limitations established by the data, a GIS-based approach to derive cross-sectional profiles was developed.

A triangulated irregular network (TIN) model of the bed was constructed for each date using a combination of bathymetric data, hand-interpolated channel bed contours, laser altimetry data, floodplain contours, and photogrammetric elevations (Church *et al*., 2001). The main advantages of the TIN model are that the data structure is based on irregularly spaced point, line and polygon data (ESRI, 1991), and that known z (elevation) values are preserved in the output model. The second step involved creating a set of lines representing the location of each desired cross-section. The lines were digitized from left to right bank (looking downstream) at roughly 400 metre spacing, or twice the spacing of the 1999 survey (see Figure 7). The endpoints of each transect were purposely placed at stable regions beyond the present (1999) channel margins so that areas of intervening bank erosion or deposition would be captured. The cross-section profiles were subsequently extracted from each TIN model in Arc/Info using the “surfacexsection” module, which interpolates elevation values at a regular user-defined spacing along each transect line. Distance and elevation values were sampled every 10 metres and recorded in a database file, then plotted. The elevation at each sampling distance is estimated from linear interpolation between known z-values except where original survey data are coincident. Given that the location of transects is based upon the 1999 survey (chosen because of the regular spacing and spatial completeness of the bathymetry survey), cross-section profiles for that year will be more representative of the actual bed surface than for the other years. A subset of the 156 cross-section profiles extracted from the TIN models (every other line) is shown in Figure 8 to Figure 17. The cross-section plots clearly illustrate the lateral and vertical instability along the river, particularly within sedimentation zones.

Each plotted cross-section is shown with a reference line which approximates the bankfull water-level surface. The area below the line, therefore, represents the active channel cross-section area and the area above the line represents island or floodplain cross-section area. The reference lines correspond to the average elevation of young island surfaces along the channel. This surface is used as an alternative to identifying vegetation trim lines directly from the mapping (i.e. the actual location of islands and floodplain, which is a standard method of defining the bankfull water-level) for two main reasons. First, the high water level along the outer banks is not always well defined, so it is convenient to use the intersection of the reference water-level and the channel profile to define the bankfull channel (eg. xs 4 and xs 6, Figure 8). In addition, high bar surfaces recently stripped of vegetation, steep unvegetated cut-banks and different ages of vegetation (eg. mature forest stands are higher in elevation relative to young willows because of increased vertical aggradation) introduce considerable natural variability in the elevation of the vegetation trim line across most cross-sections. This variability makes it difficult to

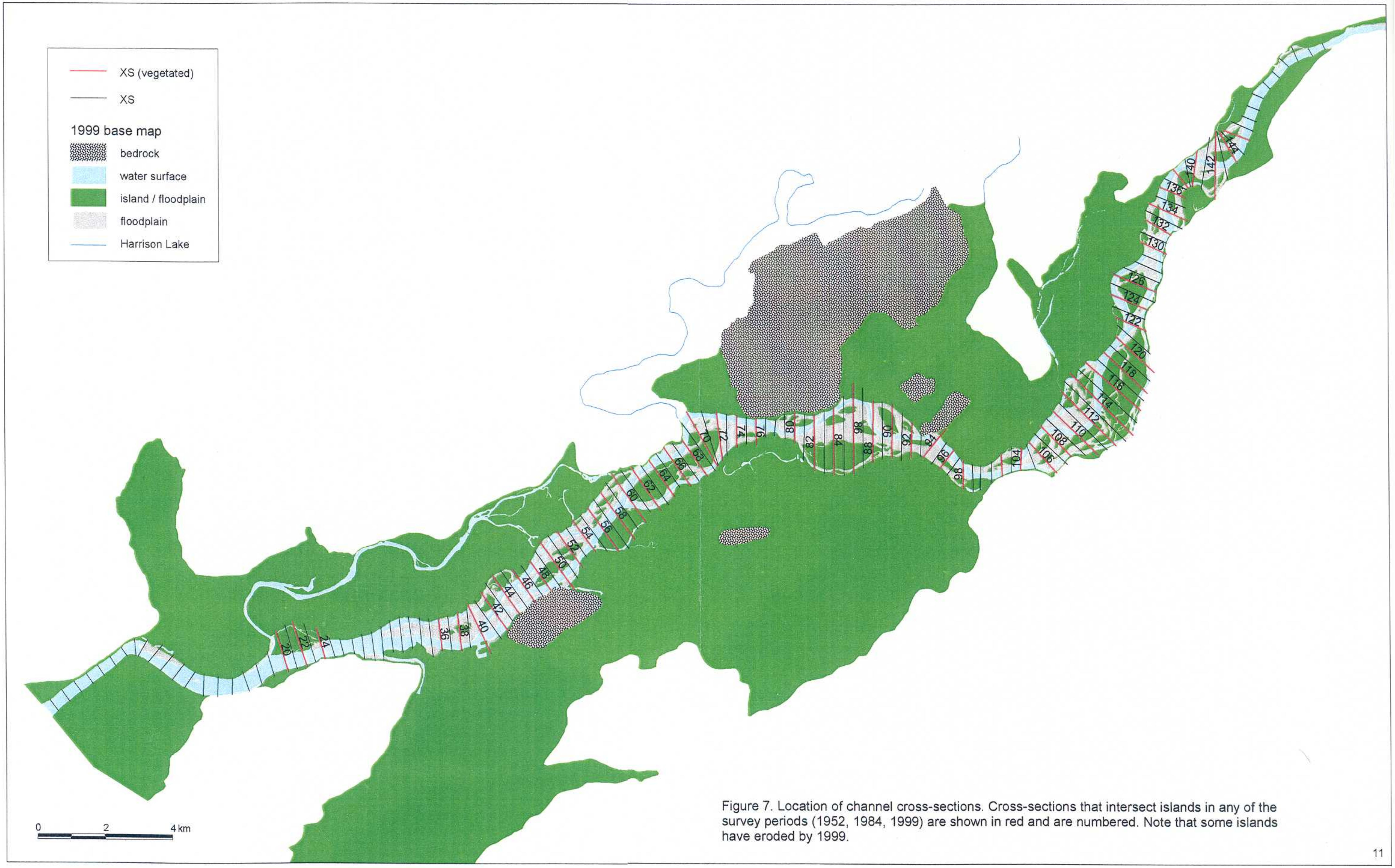

Figure 7. Location of channel cross-sections. Cross-sections that intersect islands in any of the survey periods (1952, 1984, 1999) are shown in red and are numbered. Note that some islands have eroded by 1999.

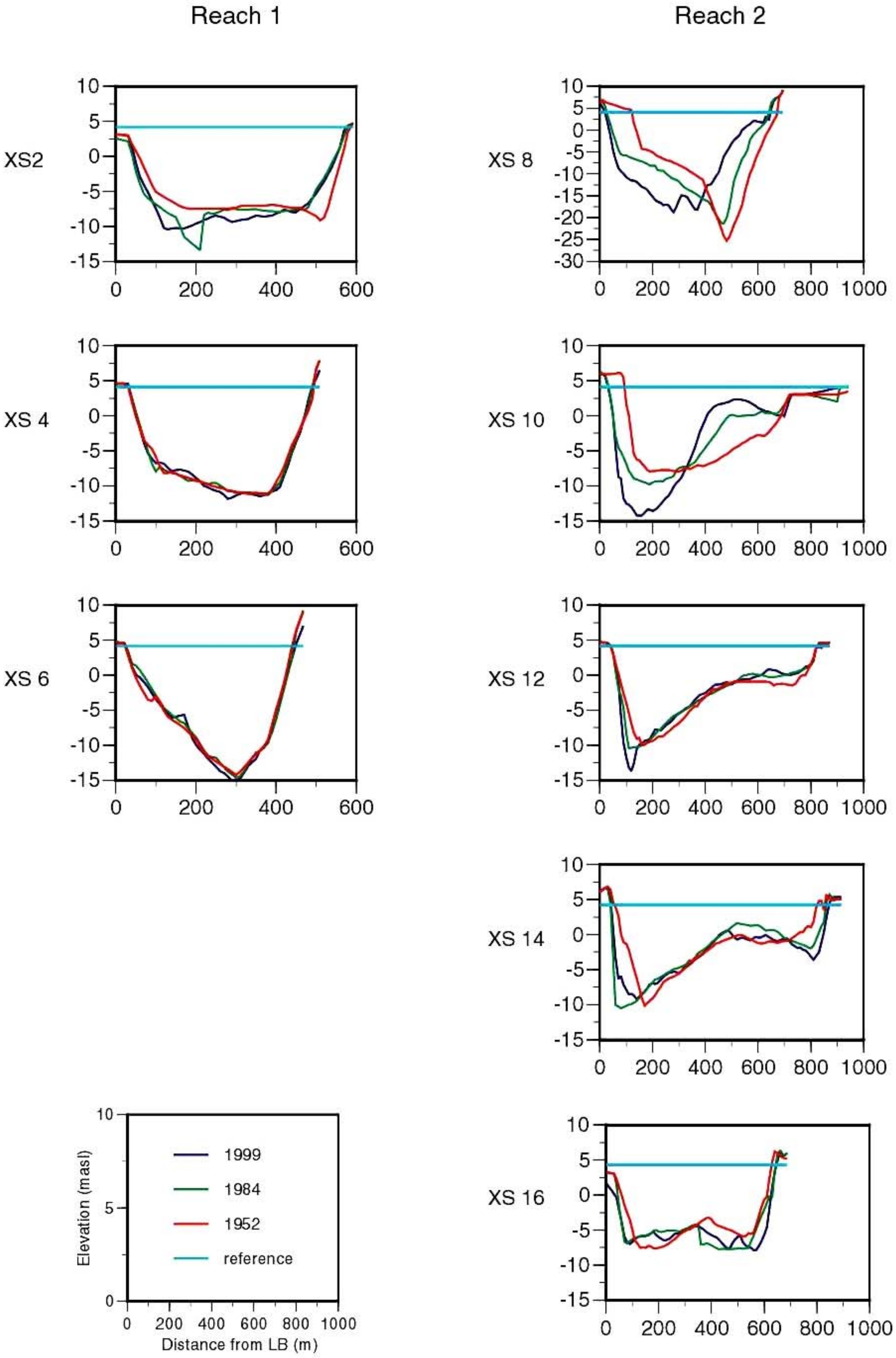

Figure 8. Channel cross-section profiles for 1952, 1984 and 1999, reaches 1 and 2.

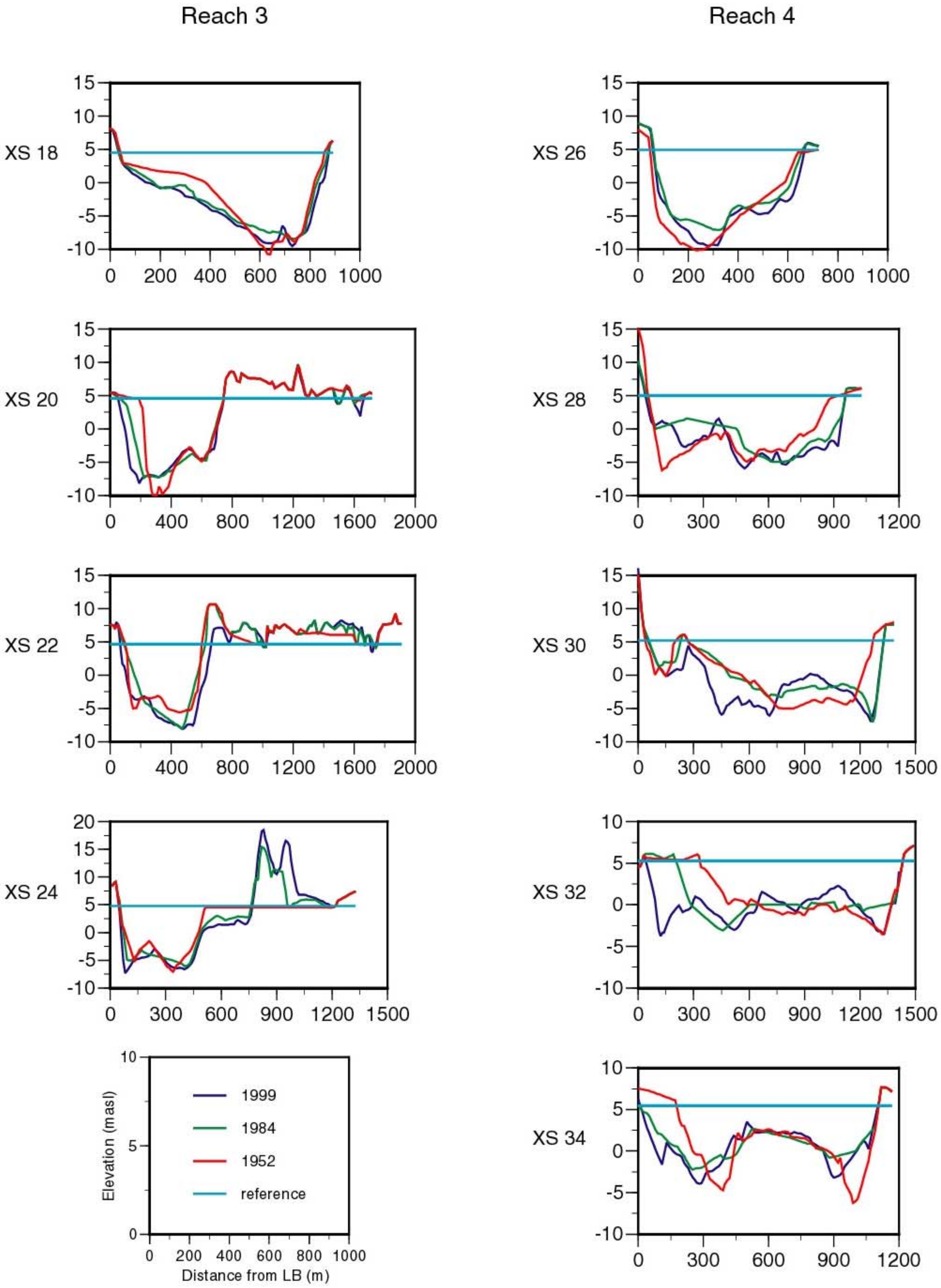

Figure 9. Channel cross-section profiles for 1952, 1984 and 1999, reaches 3 and 4.

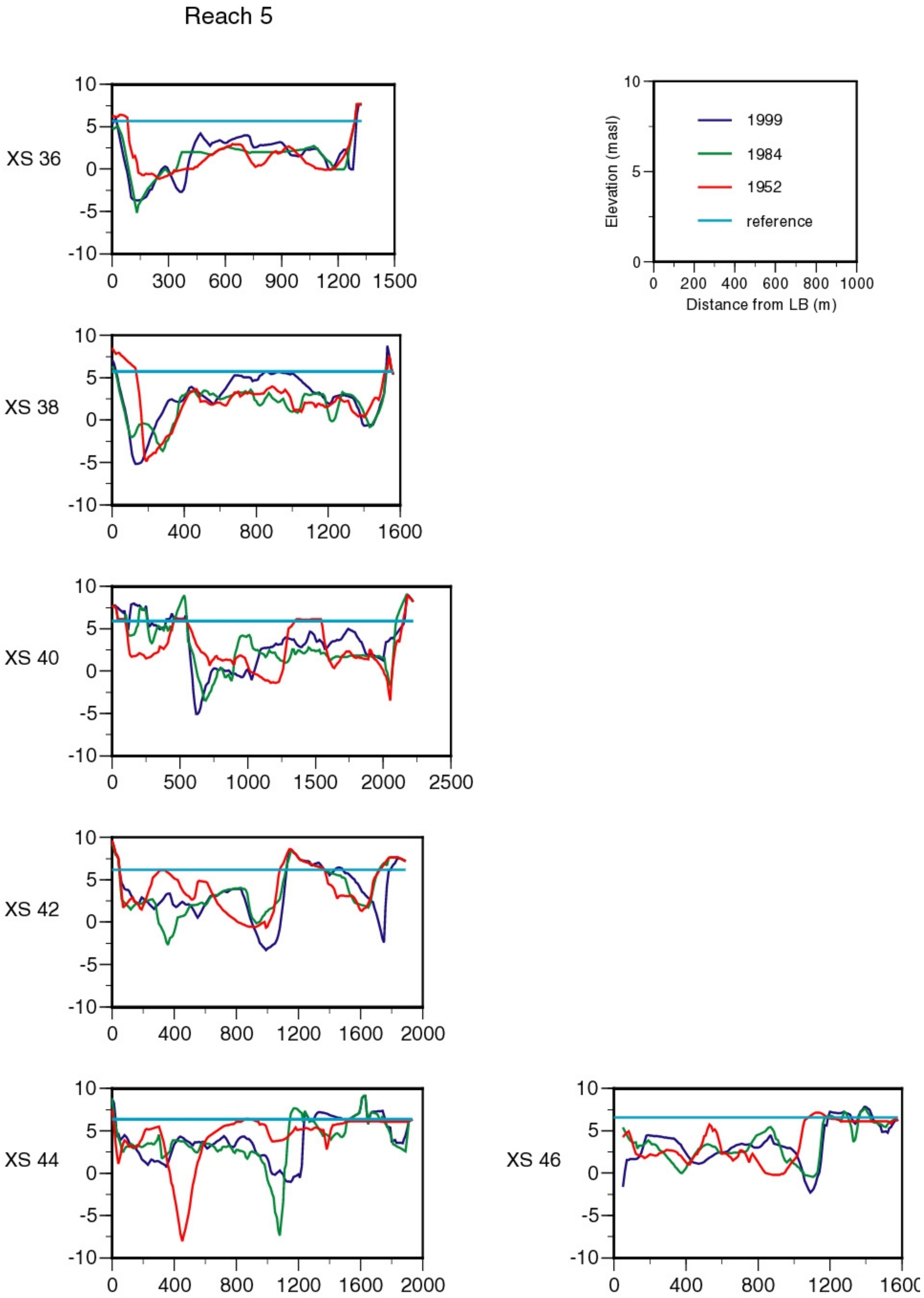

Figure 10. Channel cross-section profiles for 1952, 1984 and 1999, reach 5.

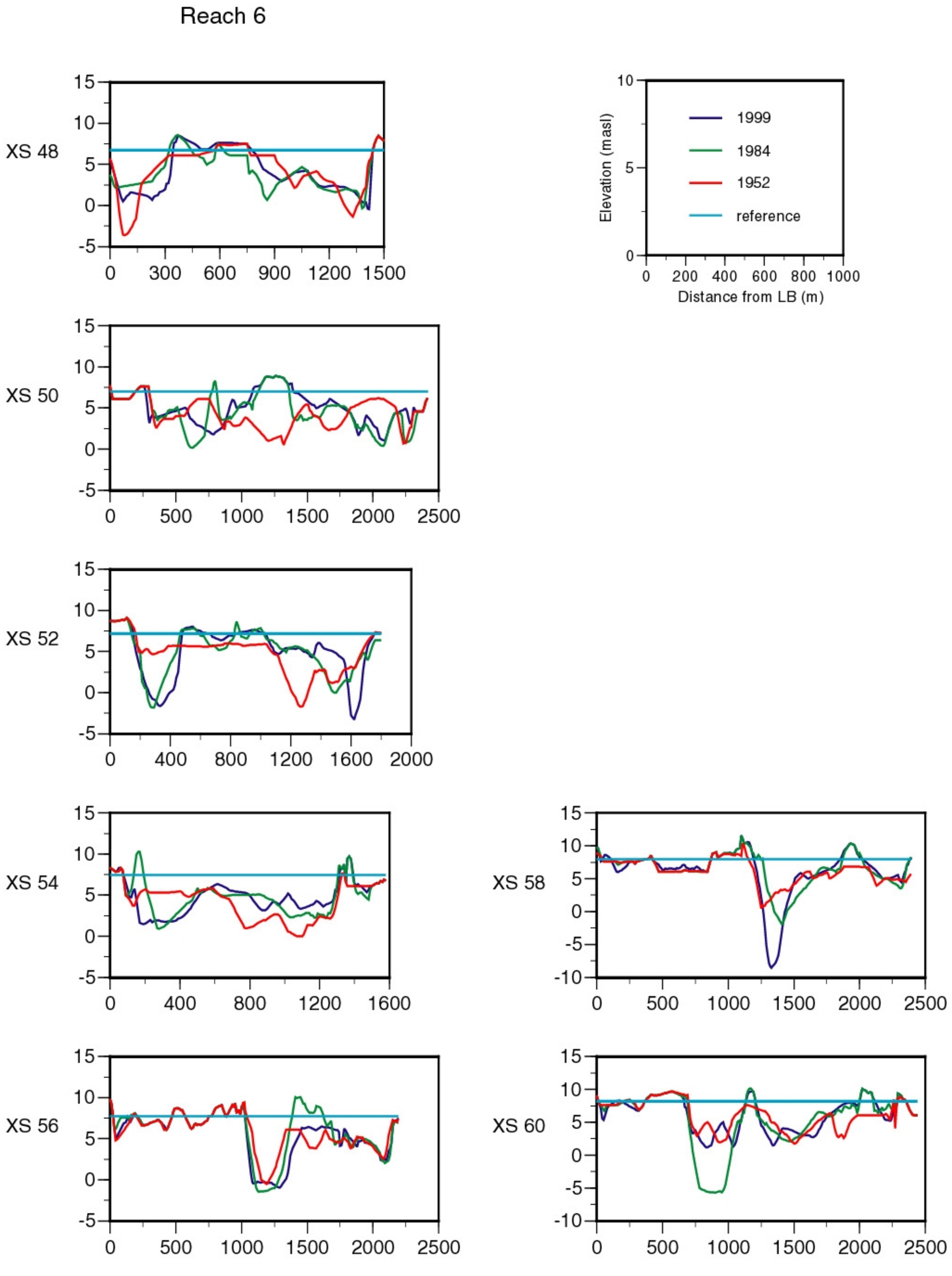

Figure 11. Channel cross-section profiles for 1952, 1984 and 1999, reach 6.

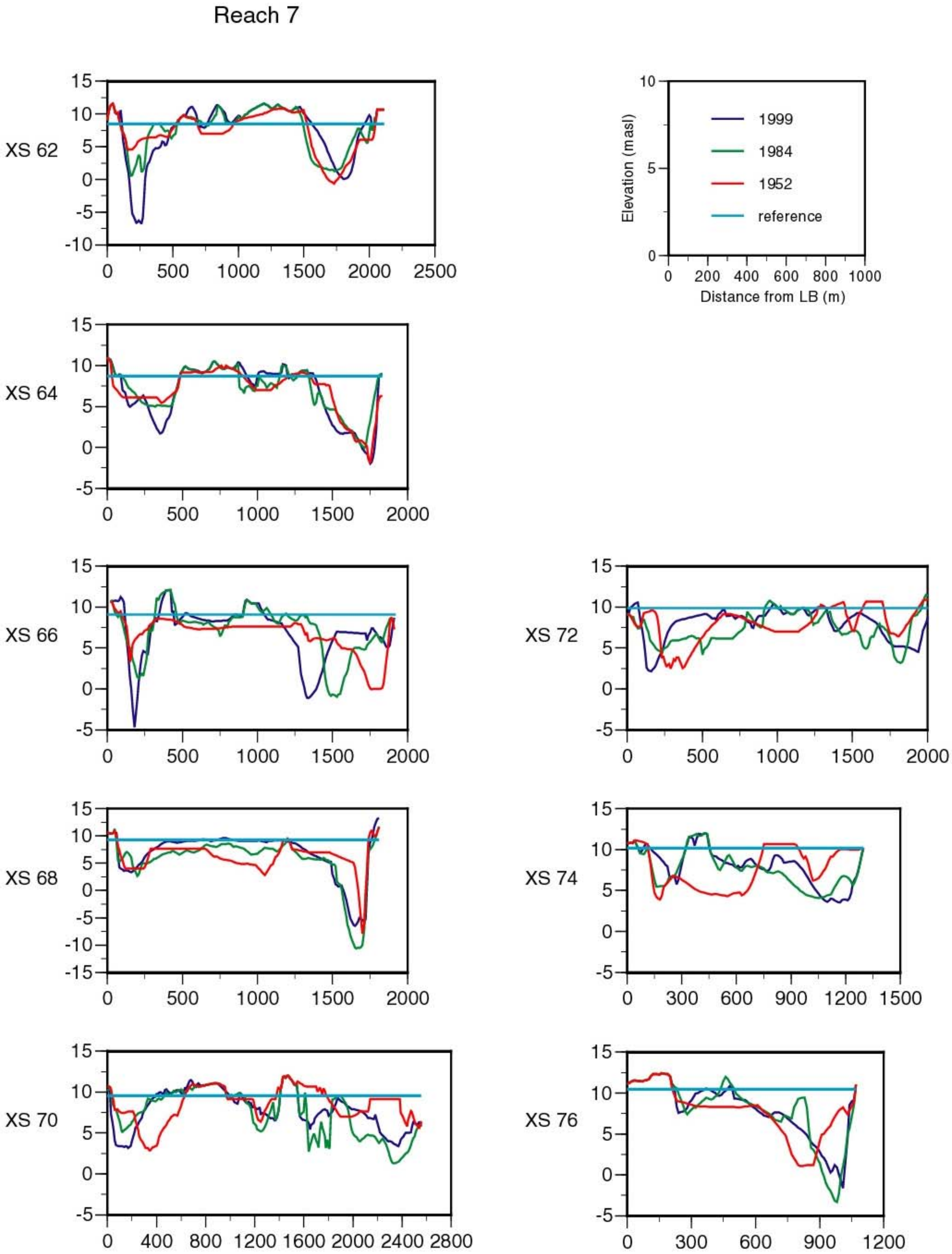

Figure 12. Channel cross-section profiles for 1952, 1984 and 1999, reach 7.

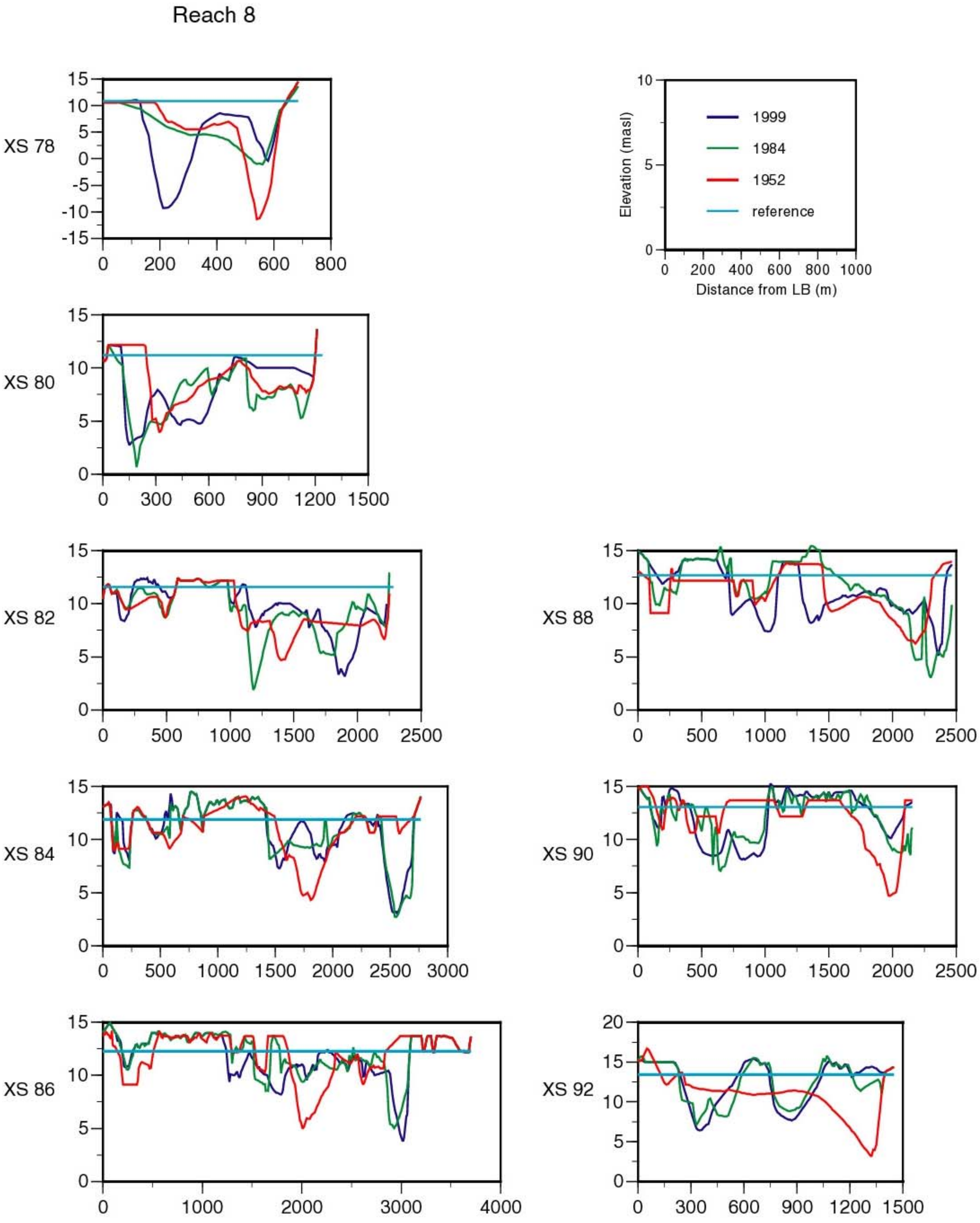

Figure 13. Channel cross-section profiles for 1952, 1984 and 1999, reach 8.

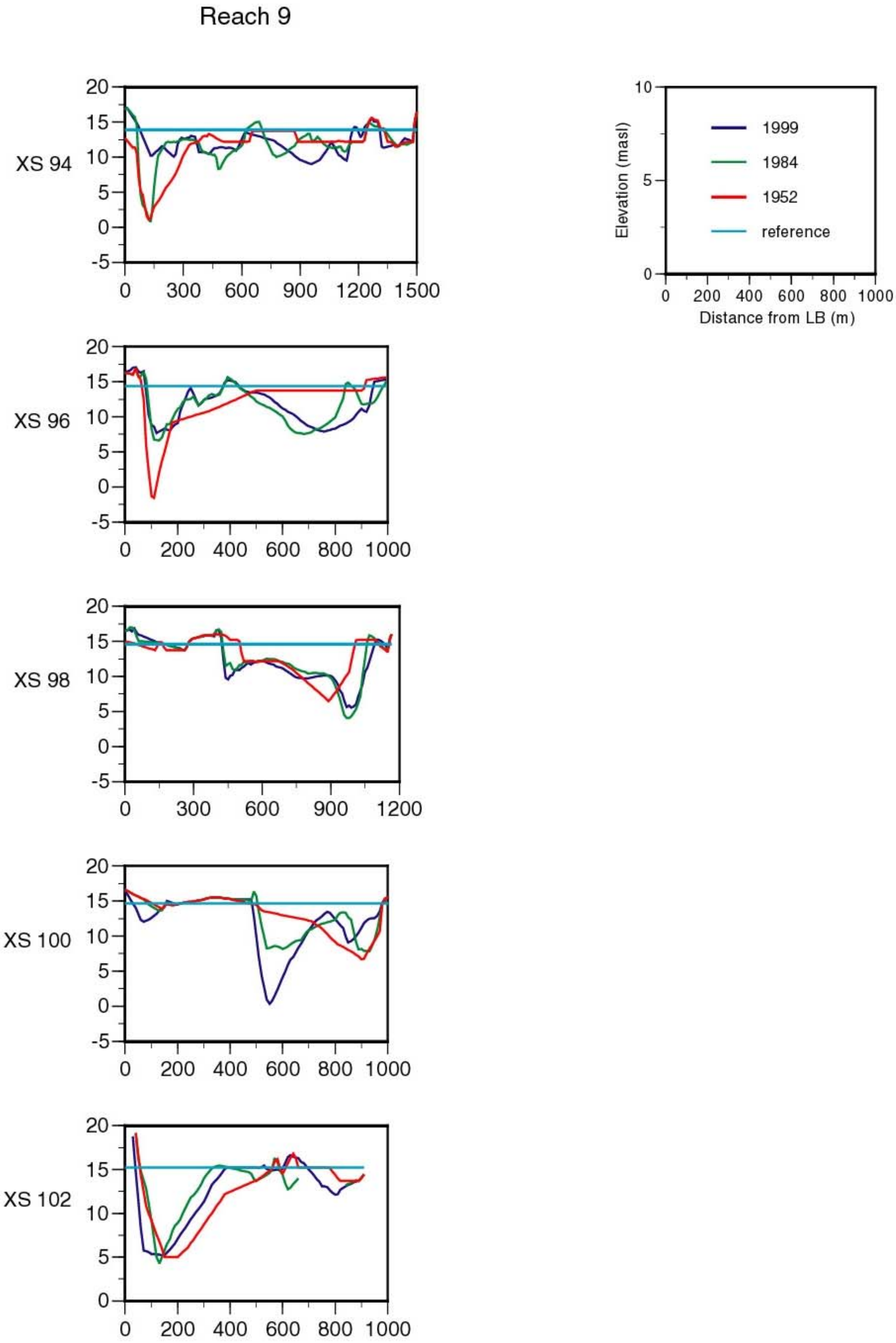

Figure 14. Channel cross-section profiles for 1952, 1984 and 1999, reach 9.

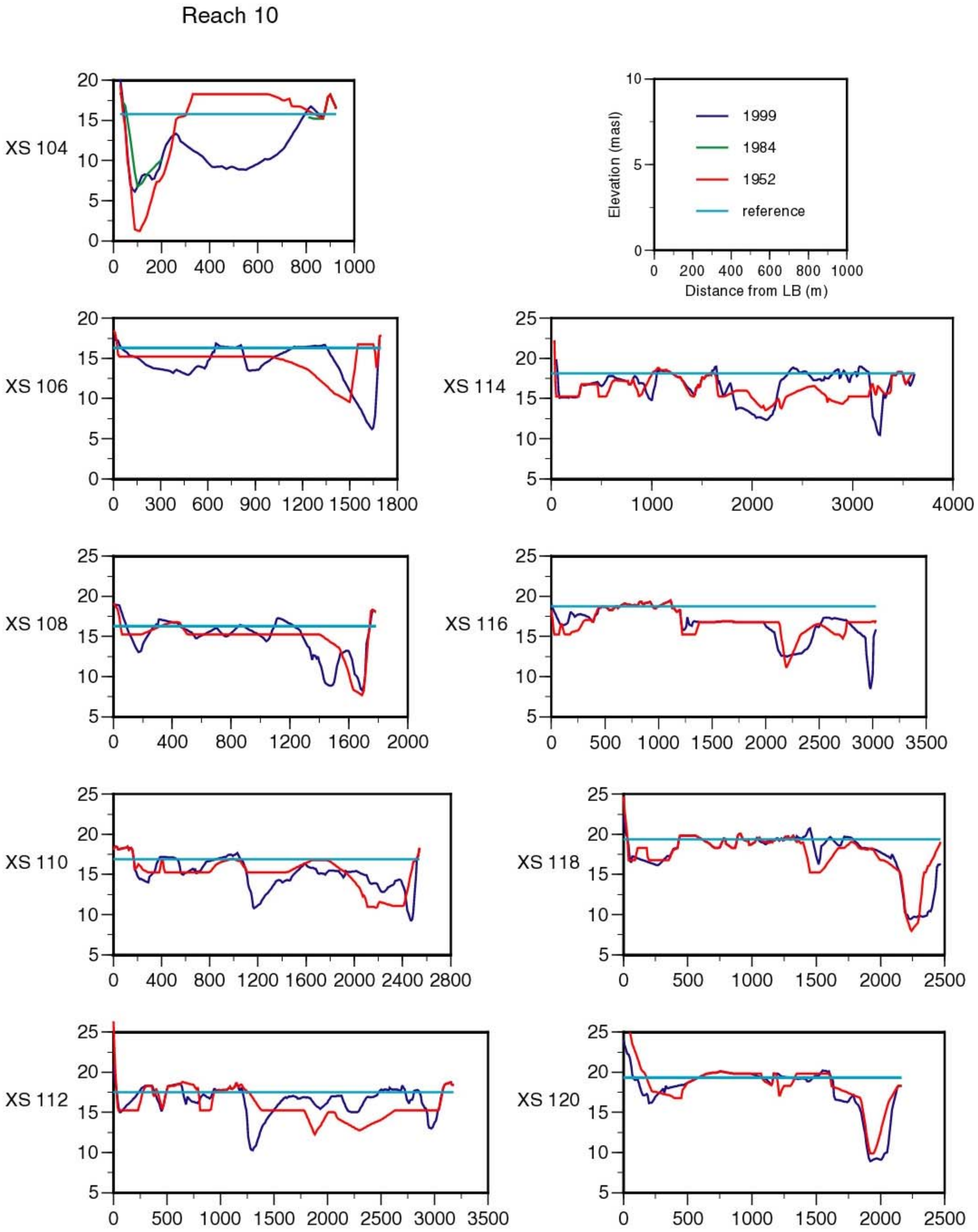

Figure 15. Channel cross-section profiles for 1952 and 1999, reach 10.

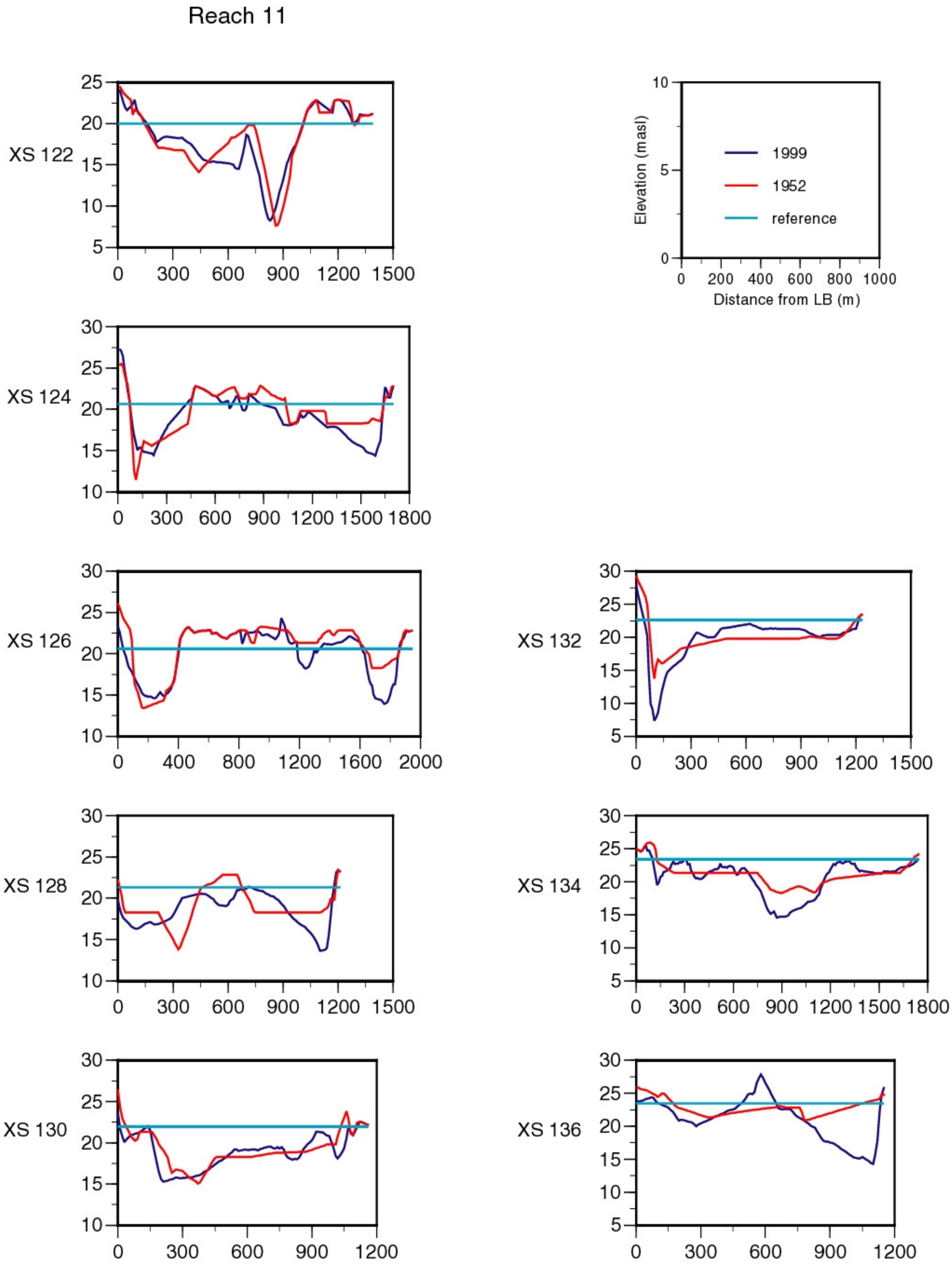

Figure 16. Channel cross-section profiles for 1952 and 1999, reach 11.

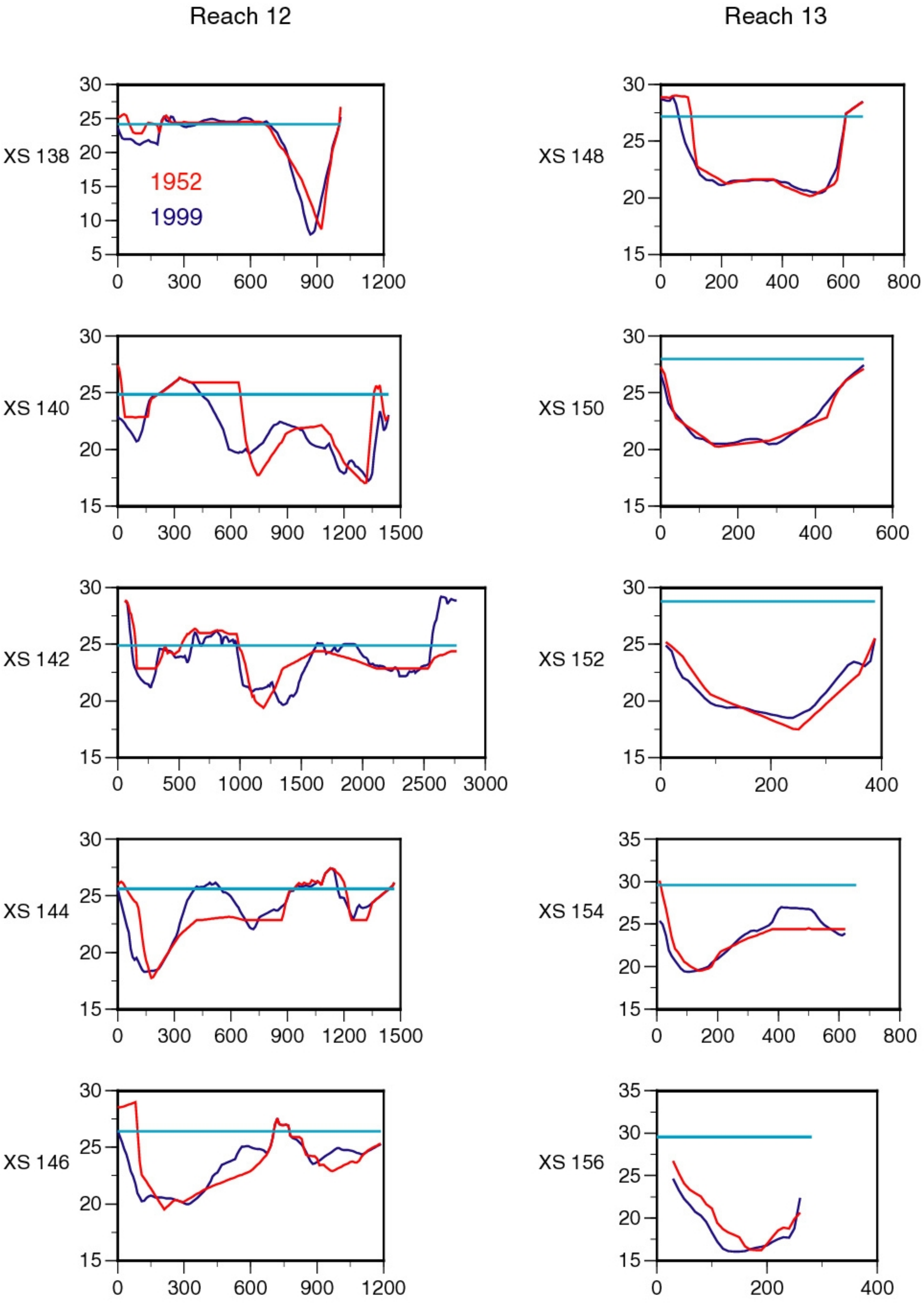

Figure 17. Channel cross-section profiles for 1952 and 1999, reaches 12 and 13.

establish an average ‘reference’ elevation along individual cross-sections and makes it difficult to compare areas above and below the reference line between survey dates.

Reference elevations were determined from laser-altimetry data collected in 1999. Channel maps for 1949, 1971 and 1999 were superimposed and coded to define three types of surfaces: old bars (polygons mapped as bars on all dates), old islands (mapped as islands/floodplain on all dates) and young islands (mapped as bars in 1971, islands in 1999). These three maps were chosen because the corresponding airphotos were all taken at low water. The coded surface map was overlaid with the laser altimetry data and average elevations were summarized for each surface along 1-km computing cells to show dowstream variability (see Figure 18). A best-fit polynomial line was drawn through the young island data to average scatter or anomalies that may occur due to vegetation age differences or insufficent data (i.e. some reaches have no islands, while others have few or no spot heights along young islands). The difference in elevation between old bar and young island surfaces represents the thickness of recent overbank (fine sand and silt) deposits, while the difference between old bar and mature islands represents the thickness of eroded overbank deposits. Previous studies (Boniface, 1985; McLean, 1990) have shown a similar association between overbank thickness and vegetation age along lower Fraser River.

The polynomial equation was used to determine reference elevations for each cross-section by solving for elevation as a function of ‘x’, where ‘x’ represents the cumulative distance between cross-sections upstream from Mission. Below xs #97, the cumulative distances for a given section were found to agree with the computing cell (e.g. xs #62 is 28.9 km upstream of Mission and located within computing cell 28). Upstream of xs #97 (morphologic reach 9), the computing cell value was substituted for x, as cumulative cross-section distances began to outpace cell values because of the increase in channel sinuosity. This leads to an overestimation of 3 km in upstream position near Laidlaw and would result in a corresponding positive bias in the reference elevation.

Active channel cross-section areas were calculated in the GIS for all even-numbered cross-sections (78 in total, refer to Figure 7). Cross-sections that intersect island surfaces were identified by comparing the location of each (1952, 1984 and 1999 surveys) with the nearest date of mapping (1949, 1983 and 1999 respectively). This was done to ensure that all transects with vegetated islands were included in the analysis – several would have been ‘missed’ by defining islands strictly based on the reference elevation since some immature islands may be lower in elevation than the reference level. It is assumed that, at any given cross-section location over time, a gain in active channel area indicates bank erosion (or a loss of vegetated area for cross-sections that intersect islands) provided that active channel width also increases. Where area increases but active channel width is unchanged or declines, the channel must become deeper. These data are illustrated in Figure 19(a to c) and summarized in Table 1 and Table 2.

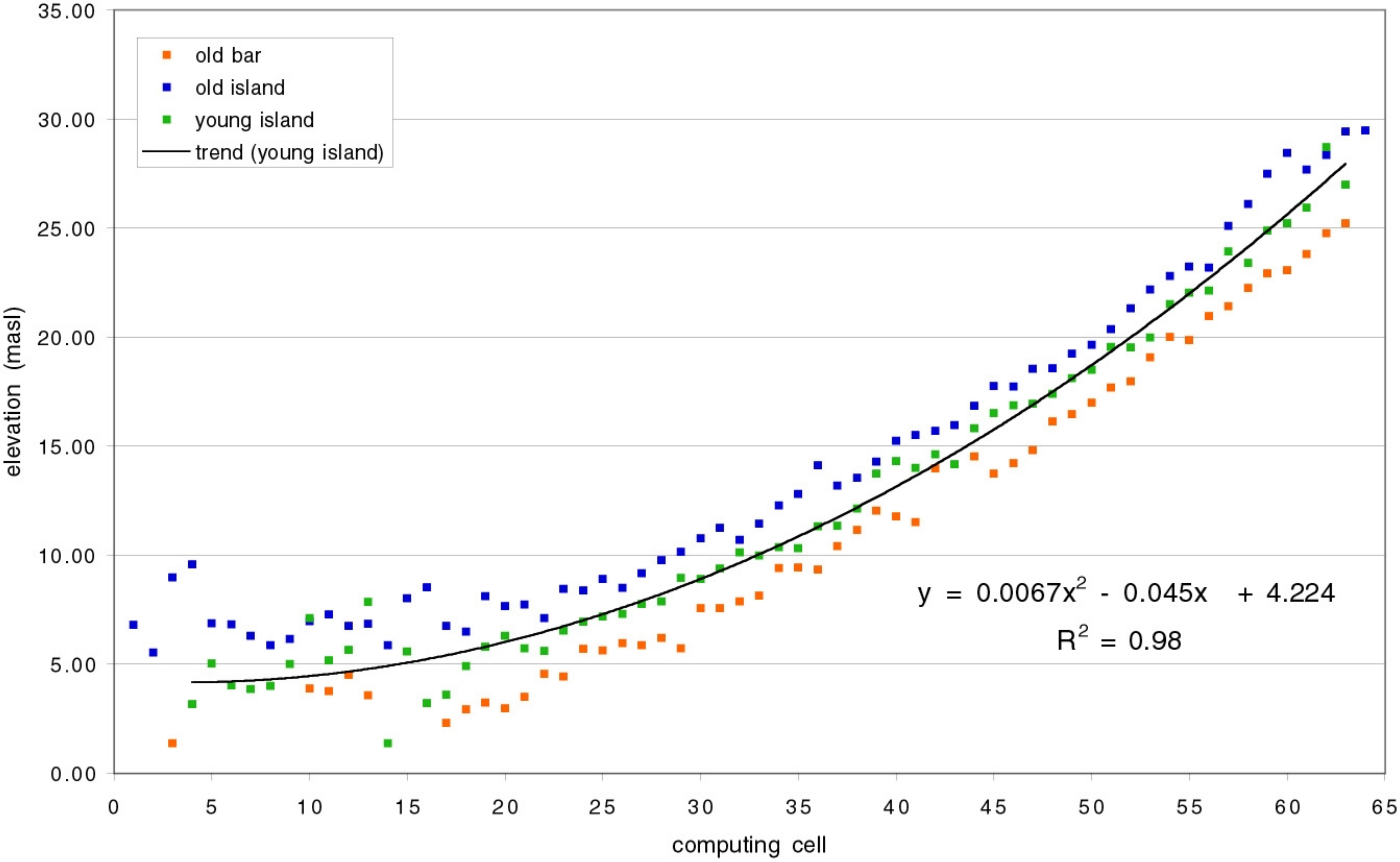

Figure 18. Relation between surface age and surface height for old bars, young islands and old (mature) islands between Mission (km 0) and Laidlaw (km 65).

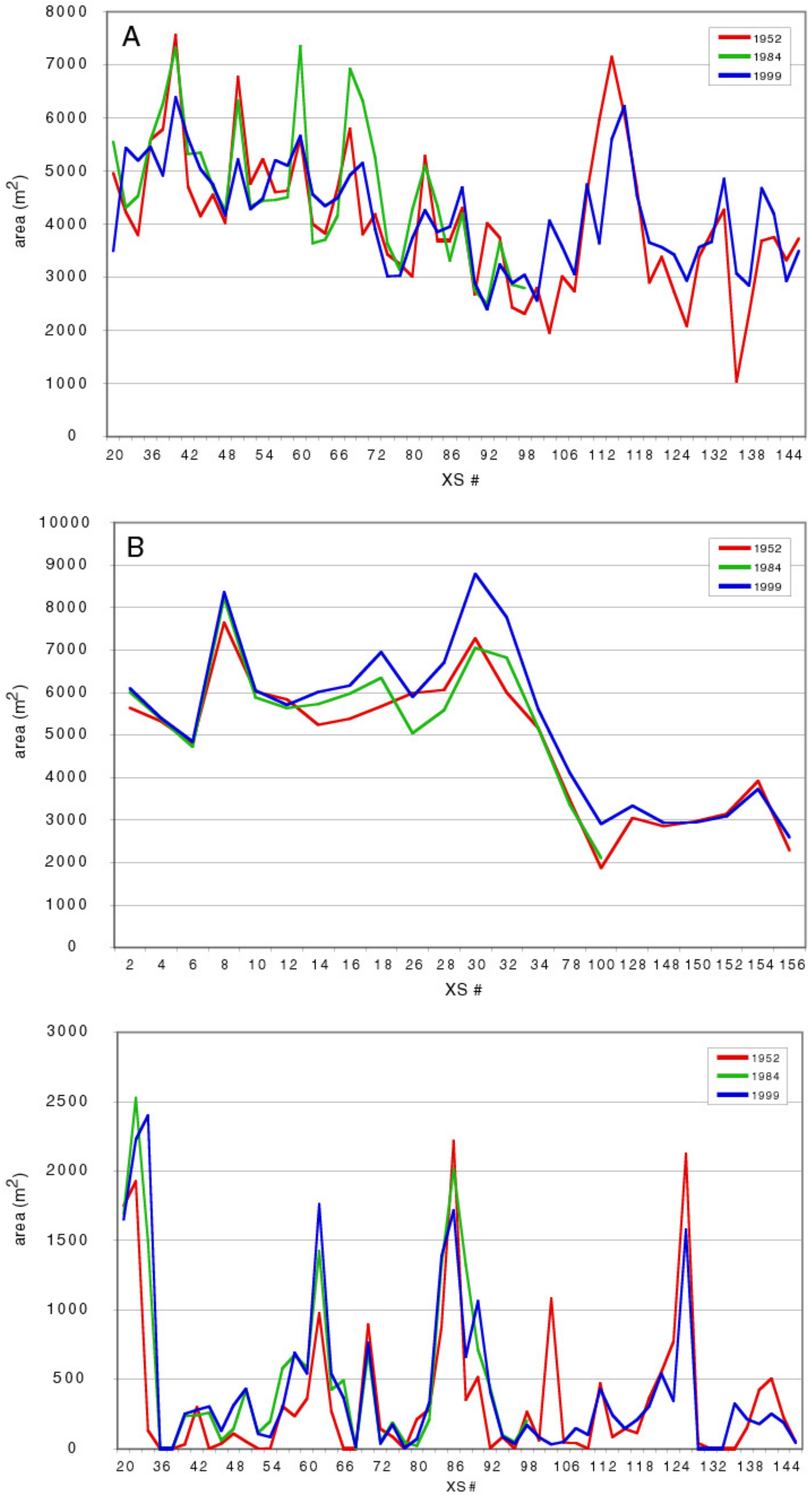

Figure 19. Active channel cross-section area (a) below reference line along x-sections with islands, (b) below reference line along unvegetated x-sections, and (c) above the reference line.

Table 1. Summary statistics for total active channel cross-section area below reference datum along sampled cross-sections

MISSION - AGASSIZ	**1952**	**1984**	**1999**
All X-sections	n = 50 $\bar{X} = 4730\ m^2$ s.d. = 1298 m^2	n = 50 $\bar{X} = 4924\ m^2$ s.d. = 1390 m^2	n = 50 $\bar{X} = 4923\ m^2$ s.d. = 1398 m^2
Vegetated (island) X-sections	n = 34 $\bar{X} = 4387\ m^2$ s.d. = 1143 m^2	n = 34 $\bar{X} = 4623\ m^2$ s.d. = 1293 m^2	n = 34 $\bar{X} = 4376\ m^2$ s.d. = 969 m^2
Unvegetated X-sections	n = 16 $\bar{X} = 5460\ m^2$ s.d. = 1340 m^2	n = 16 $\bar{X} = 5563\ m^2$ s.d. = 1412 m^2	n = 16 $\bar{X} = 6085\ m^2$ s.d. = 1482 m^2
AGASSIZ - LAIDLAW	**1952**	**1984**	**1999**
All X-sections	n = 28 $\bar{X} = 3485\ m^2$ s.d. = 1310 m^2	n.d.	n = 28 $\bar{X} = 3695\ m^2$ s.d. = 894 m^2
Vegetated (island) X-sections	n = 28 $\bar{X} = 3608\ m^2$ s.d. = 1437 m^2	n.d.	n = 22 $\bar{X} = 3858\ m^2$ s.d. = 928 m^2
Unvegetated X-sections	n = 6 $\bar{X} = 3033\ m^2$ s.d. = 528 m^2	n.d.	n = 6 $\bar{X} = 3100\ m^2$ s.d. = 392 m^2

Table 2. Summary statistics for total vegetated (solid) x-section area above reference datum along sampled cross-sections

MISSION - AGASSIZ	**1952**	**1984**	**1999**
Vegetated (island) X-sections	n = 28 $\bar{X} = 443\ m^2$ s.d. = 603 m^2	n = 31 $\bar{X} = 610\ m^2$ s.d. = 654 m^2	n = 32 $\bar{X} = 602\ m^2$ s.d. = 675 m^2
AGASSIZ - LAIDLAW	**1952**	**1984**	**1999**
Vegetated (island) X-sections	n = 19 $\bar{X} = 381\ m^2$ s.d. = 513 m^2	n.d.	n = 19 $\bar{X} = 284\ m^2$ s.d. = 341 m^2

The significance of changes in cross-section area over time can be determined through a statistical comparison of cross-section mean and variance values. In a natural channel that exhibits complex morphology, there is sufficient variation in cross-section areas along the channel such that some sections are larger, on average, than the mean area, while others are smaller. Furthermore, if the complexity of channel morphology is changing, then the size of these deviations from the mean (i.e. the variance) may also change. Change in these properties must be tested separately. A summary of the significance of difference in the mean and variability of cross-section areas is given in Table 3 (area below reference datum) and Table 4 (area above reference datum).

Table 3. Tests for significant differences between mean (t) and variance (f) of active channel cross-section area below the high water reference line. P is the probability that the test statistic is less than the critical value (critical values are italicized in bold).

MISSION - AGASSIZ	1952-84		1984-99		1952-99	
All X-sections	F = 1.15 p = 0.32	t = 0.72 p = 0.47	F = 1.01 p = 0.48	t = 0.002 p = 0.999	F = 1.16 p = 0.30	t = 0.72 p = 0.48
Vegetated (island) X-sections	F = 1.28 p = 0.24	t = 0.80 p = 0.43	F = 1.78 ***p = 0.05***	t = 0.89 p = 0.38	F = 1.39 p = 0.17	t = 0.04 p = 0.97
Unvegetated X-sections	F = 1.11 p = 0.42	t = 0.21 p = 0.83	F = 1.10 p = 0.43	t = 1.02 p = 0.32	F = 1.22 p = 0.35	t = 1.25 p = 0.22
AGASSIZ - LAIDLAW	All XS		Vegetated		Unvegetated	
1952 - 99	F = 2.15 ***p = 0.03***	t = 0.70 p = 0.49	F = 2.40 ***p = 0.03***	t = 0.68 p = 0.50	F = 1.82 p = 0.26	t = 0.25 p = 0.81

Table 4. Tests for significant differences between mean and variance of island cross-section area above the high water reference line

1952-84		1984-99		1952-99		1952-99	
MISSION - AGASSIZ		**MISSION - AGASSIZ**		**MISSION - AGASSIZ**		**AGASSIZ-LAIDLAW**	
F = 1.18 p = 0.34	t = 1.13 p = 0.26	F = 1.07 p = 0.43	t = 0.03 p = 0.97	F = 1.25 p = 0.28	t = 1.08 p = 0.29	F = 2.27 ***p = 0.05***	t = 0.69 p = 0.50

Mean active channel area between Mission and Agassiz was larger in 1984 than in 1952 along both vegetated and unvegetated cross-sections, although these differences are not statistically significant. Flood flows were, on average, larger during the period 1948-77 than in subsequent years (see McLean and Church, 1999) which is consistent with the observed active channel widening during this period (Figure 3a). The total area of channel islands also declined because of bank erosion, although much of the decrease can be directly attributed to islands becoming cut-off from the active channel zone by flood and erosion control structures (i.e. they became part of the terrestrial floodplain). In fact, island area above the high water line actually increased to 1984, although not significantly. Nevertheless, as the channel was actually slightly narrower in 1984 than in 1952, there must have been some deepening of the channel (relative to the reference level) to maintain flow conveyance.

Between 1984 and 1999, mean cross-section area declined amongst the islands, but increased along the unvegetated sections of channel. However, these changes balanced overall such that the mean area of all cross-sections did not change downstream of Agassiz. The decrease in active channel area along the vegetated cross-sections is consistent with the observed increase in island area since 1977 as the magnitude of flood flows has generally been below average since then. However, the area above the reference line did not also increase, so development of young, lower elevation island and floodplain surfaces, presumably the consequence of reduced flooding, accounts for the change. There is also evidence (though weak statistically) that the variability of cross-section area has been decreasing along the islands. These findings suggest that islands are becoming larger, but less numerous (i.e. fewer small islands). Channel width has also declined since 1977 and the channel was narrower in 1999 than in any previous period (an overall decrease of 8%, or 82 metres since 1949). Given that active channel area did not also decrease, the channel must have deepened. Average channel depth can be estimated by dividing the mean active channel cross-section area by the mean active channel width. This gives an average channel depth of 4.84 m in 1952, 5.07 m in 1984 and 5.50 m in 1999.

Upstream of Agassiz, mean active channel area increased along both vegetated and unvegetated cross-sections between 1952 and 1999, although the difference is, again, not statistically significant. However, there was a significant decrease in area variability for the vegetated cross-sections (and overall). Island area also increased along most upper reaches, suggesting fewer, but larger islands, a pattern of morphologic development similar to that observed downstream (the significant decrease in the variability of island area above the high water line supports this inference). Most upper reaches were narrower in 1999 than in 1952 and overall channel width declined 18%, resulting in an average increase in channel depth from 3.53 to 4.55 metres. That the channel appears to be deepening more quickly along upper reaches than downstream reaches is also consistent with the observation of channel degradation in this reach (Church et al., 2001).

Overall, the channel is narrower and deeper today than 50 years ago and islands have increased in total area (although cross-section area has not changed along vegetated cross-sections below Agassiz). Nevertheless, observed changes are merely indicative of *trends* in channel behaviour, rather than proof of any particular mechanism. Given that changes in the long-term flow regime appear to influence changes in channel morphology, it is difficult to isolate the impacts of human disturbance.

Longitudinal profiles

Current evidence suggests that upper reaches of lower Fraser River are degrading, and that material is mobilised there and transported further downstream. This pattern of erosion and deposition should correspond with a change in channel slope and alter the shape of the longitudinal profile. These characteristics represent an additional means of channel form adjustment. Longitudinal profiles for the channel bed were constructed for 1952, 1984 and 1999 from available survey data and from three-dimensional modeled surfaces. Prior to extracting profile data, it was first necessary to define the thalweg for each survey. For each model, a set of bathymetric contours was produced, then overlaid on a morphologic map from the closest available date. The thalweg lines were subsequently hand-digitized following the most probable flow path between islands and exposed bars. This method may result in small positional errors in thalweg placement but produces a smoother, more contiguous (hence realistic) path than one which follows the lowest elevation point along each survey transect. Thalweg profiles for each date of survey are given in Figure 20. These profiles display the characteristic ‘irregularly sinuous’ pattern associated with wandering gravel-bed channels. The thalweg has remained remarkably fixed upstream of Herrling Island and downstream of Chilliwack Mountain because there is little deposition of gravel at those locations. Within the depositional reach, the thalweg is observed to have both migrated and avulsed over the past 50 years.

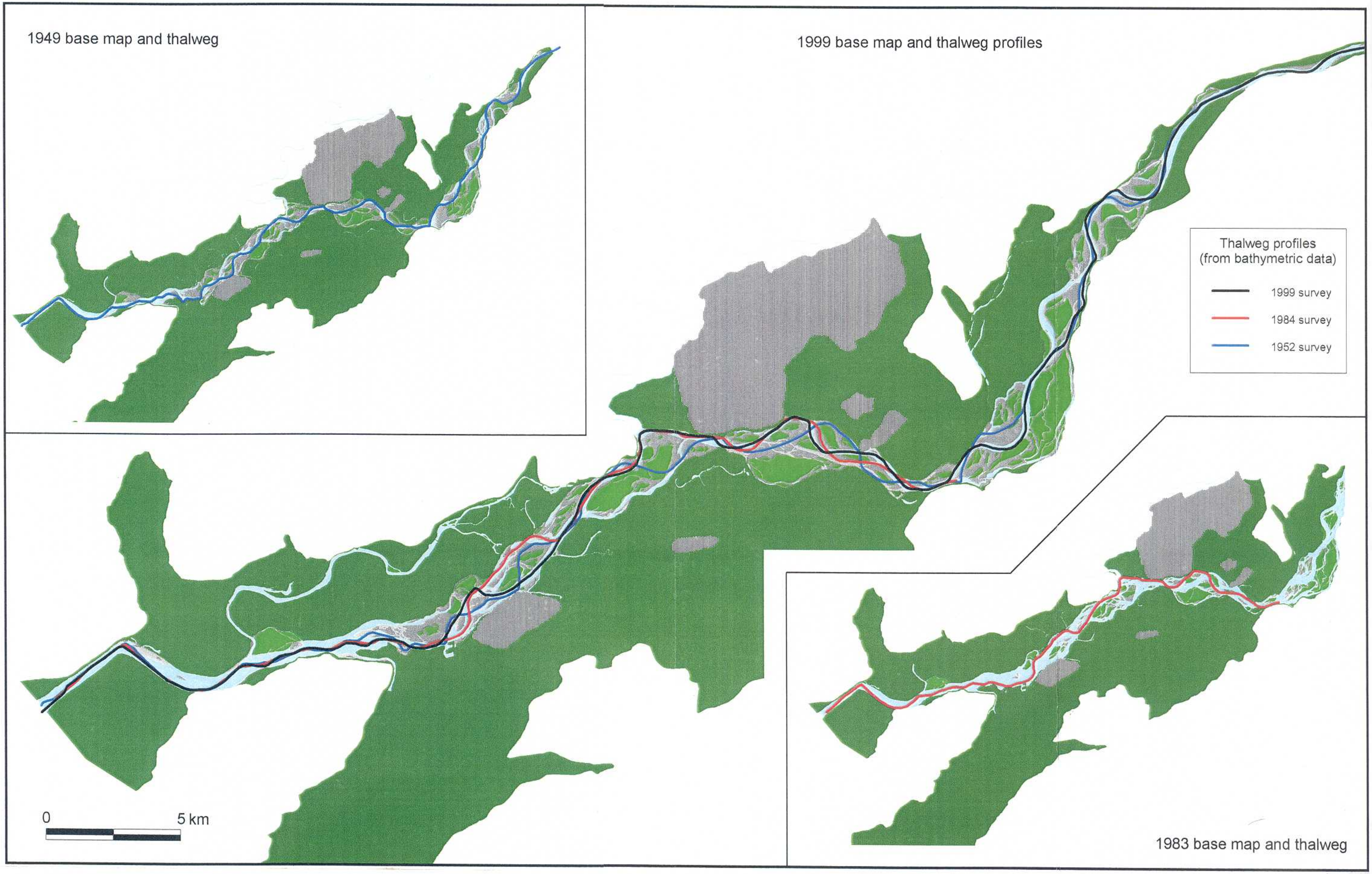

Figure 20. Thalweg profiles for 1952, 1984 and 1999 from bathymetric data

The following step in the analysis involved selecting the bed elevation (point) along each transverse survey line nearest to the thalweg. These points were manually selected in the GIS and written to a separate file. Where the density of sounding points was inadequate to represent the natural curvature of the thalweg (1952 and 1984 surveys only), additional points were added and assigned an elevation based on either the nearest available contour line (1952 survey) or from the interpolated grid models (1952, where contour spacing was inadequate, and 1984 surveys). The geographic coordinates and elevations of all sampled points were then exported to a spreadsheet to measure the distance between adjacent points. Elevations at cumulative distances downstream represent the long profile of the channel. The resulting plot of these data clearly displays a pattern of alternating riffle and pools, several of which are very deep (see Figure 21). A water surface profile taken at the time of the 1999 bed survey is given for additional reference (surface elevations are unavailable for the other dates). The 'flattening' of the water surface that begins roughly 55 km downstream (below Chilliwack Mountain) represents the initial transition zone where sand becomes the dominant bed sediment.

Although it is clear that some riffles and pools have remained remarkably stable over time, much of the bed is unstable. The observed instability results from migration of the thalweg in response to the staging of bed material downstream. Stable pools (refer to examples in Figure 21) are typically found near the bank along the outside edge of sharp bends within confined sections of channel, where little bed material is deposited. Unstable pools are similarly found along the outside edge of bends, but within sedimentation zones, so pools become filled as bars migrate downstream. Although there is no clear pattern associated with these plots, careful examination reveals a decrease in the number of very deep pools between 1952 and 1999. This becomes more apparent when the plots are superimposed (Figure 22). It is also apparent that several major riffle zones have increased in height and topographic variability (i.e. the range between minimum and maximum depths) has decreased over time, particularly below the Harrison confluence. These characteristics are indicative of a simplification in channel morphology.

A simple means of determining whether channel slope has been changing is to model the slope trend along the long profiles using linear regression. These results indicate that mean channel slope has decreased from 4.58 to 4.46 m / km between 1952 and 1999. This result is consistent with upstream degradation and downstream aggradation, but the analysis may be biased by a few outlying values. A more robust approach involves calculating the area below the bed surface defined by the thalweg, a procedure analogous to comparing repeated cross-sections. For each profile, a polygon was constructed above an arbitrary base level (here, -30 m.a.s.l.) along the profile length with verticals at the endpoints (see Figure 23). The endpoints were chosen at distances common to all surveys. The upstream bound of the 1984 survey was used to define separate upstream and downstream polygons for the longer 1952 and 1999 profiles. Polygon areas are summarized in Table 5.

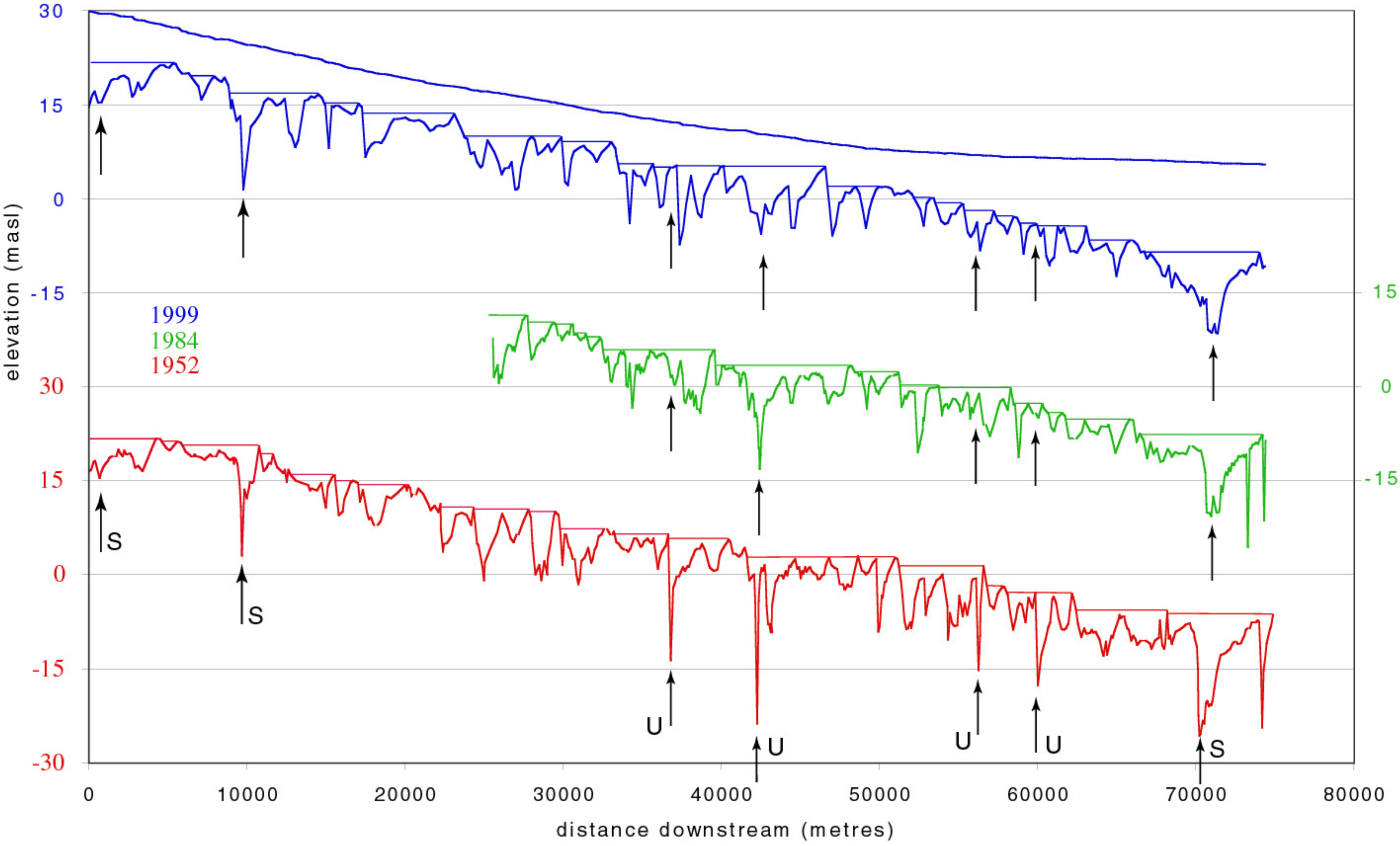

Figure 21. Longitudinal profiles showing alternating riffles and pools along thalweg of lower Fraser River.

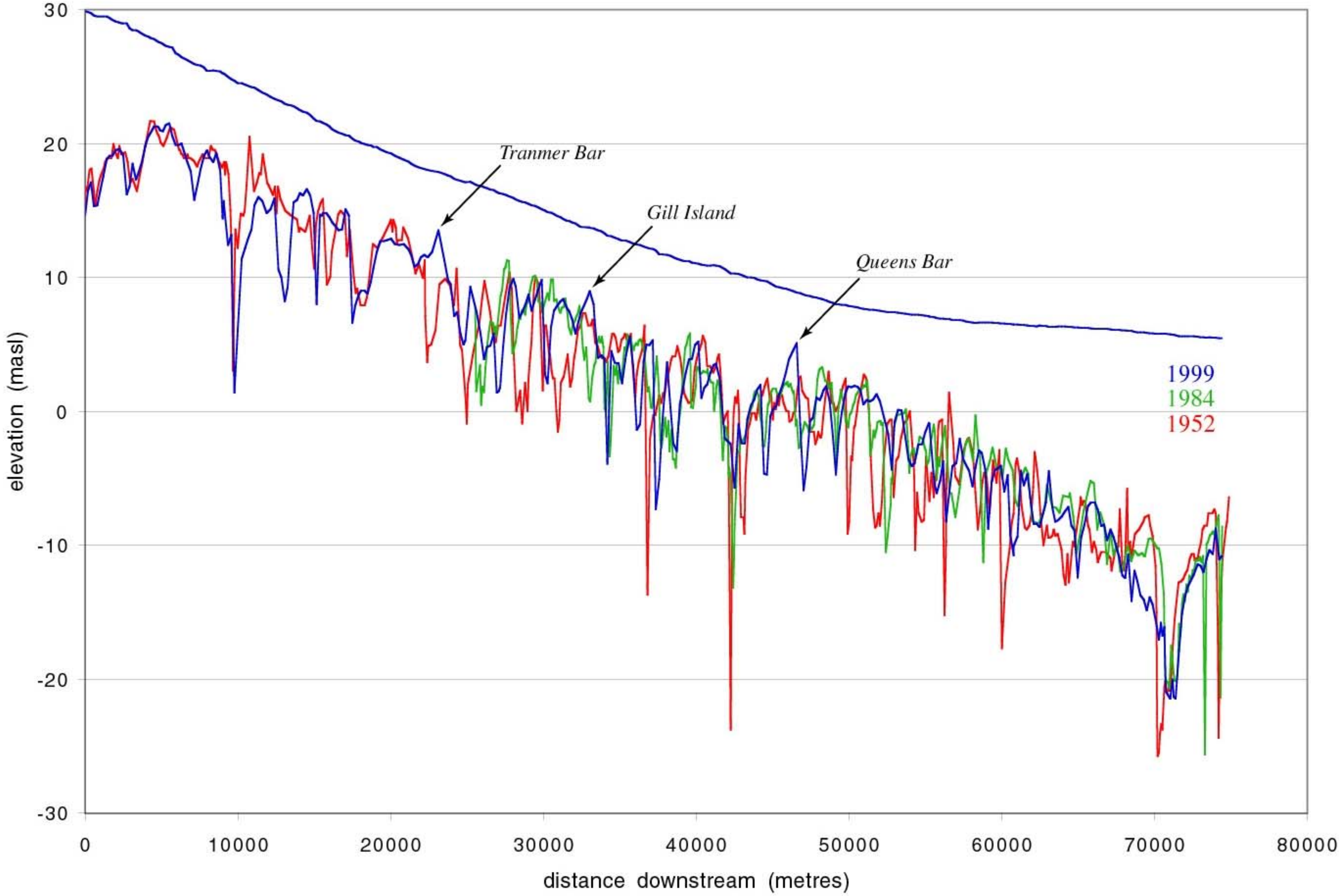

Figure 22. Superimposed longitudinal thalweg profiles showing variability in the location of riffles and pools.

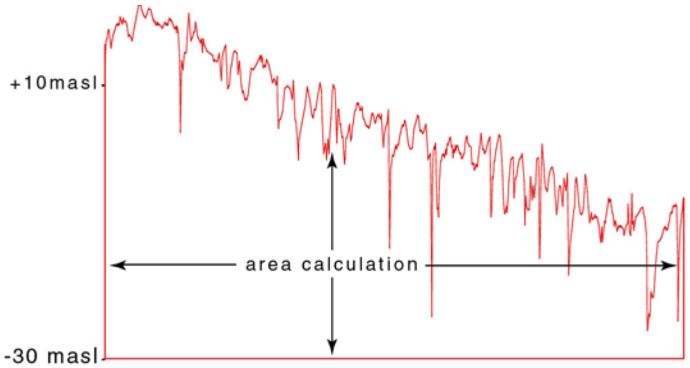

Figure 23. Sketch to show calculation of the area below the bed surface along thalweg. An increase in area between surveys indicates aggradation along the thalweg; a decrease indicates degradation.

Table 5. Calculated area below longitudinal profiles as measured along thalwegs

	1952	1984	1999
u/s Agassiz	1.141 x10^{6} m^{2}	-	1.134 x10^{6} m^{2}
d/s Agassiz	1.333 x10^{6} m^{2}	1.364 x10^{6} m^{2}	1.353 x10^{6} m^{2}
total	2.474 x10^{6} m^{2}	-	2.487 x10^{6} m^{2}

Upstream of Agassiz, polygon area decreased from 1952 to 1999, indicating that the average thalweg lowered through degradation. In contrast, the thalweg became raised along the downstream reach. Although comparison is compromised by the limited spatial coverage along the channel bed, it is consistent with the previously reported pattern of sediment transport within the gravel reach (Church *et al*., 2001). The sediment budget (which is not limited by spatial bias because it covers the complete extent of he channel bed and banks) shows bed material degradation within the active channel zone upstream of Agassiz, and aggradation downstream. Aggradation is also observed along the thalweg downstream of Agassiz from 1952 to 1984 (although active channel area increased) while degradation occurred by 1999 (active channel area was unchanged) reflecting adjustments in active channel width. For comparison, the sediment budget shows that active channel zone was aggrading in both periods.

4.0 DISCUSSION

Repeat aerial photography and bathymetric surveys completed over the past half-century permit a detailed examination of changes in channel morphology over this time. Analysis of data from these surveys reveals a number of significant trends, including:

- the channel is becoming narrower
- the channel is becoming deeper
- the area of channel islands is increasing

The morphology of a channel is dominated by the flux of water and sediment through the system. Active channel zone width does not appear to be strongly correlated with bank erosion and deposition over the long term since lateral and volumetric rates of change roughly balance. Channel narrowing and island growth are consistent with long-term trends in flow. During extended periods of below-average floods (for example, 1977 to present) vegetation becomes established or matures on elevated bar surfaces, creating new island area. It is also possible that bed material influx (especially sands) to the reach is being increasingly deposited along or adjacent to high bar and island surfaces, rather than within the main flow channel. This circumstance would further account for the increase in island growth (mainly in area, but also in height), as more vegetation traps more sediment and new plants establish (i.e. a positive feedback develops). A narrowing, deepening channel is also consistent with an increase in bank hardening over the past half-century. However, the river system is so large that these impacts may be partly absorbed without visible effect, although it is equally likely that the river remains in a state of disequilibrium response as the full magnitude of past (and continuing) disturbances continues to modify channel evolution.

The longer term implication of the current pattern of channel development is infilling of side-channels between islands and coalescence into ‘mega-islands’. These effects are amplified during periods of below-average flood flows and greater interannual variability, both of which are observed in recent decades (McLean and Church, 1999). Flood flows have also been gradually decreasing in size since 1912 (when the river was gauged) but the decrease is sufficiently small (3.6 % over 88 years) that morphology has likely not been influenced. Fluctuating flow trends are expected to continue in the future.

In coming decades, a reduction in water and sediment supply to the river is expected to increasingly force the river from a multiple channel system divided around large forested islands to a single thread meandering system with lower overall ecological diversity. It is important to note that this report provides evidence that such a shift may already be underway. The reduction of channel instability associated with reduced flood flows and sediment transfers promotes vegetation growth and islands eventually become attached to the adjacent floodplain. While this does not decrease the actual vegetated surface area *along* the channel, the transition of islands to floodplain reduces morphologic, hence ecologic complexity *within* the channel as the total edge length of islands is eventually reduced. A continuation of aerial photography and bathymetric surveys will be necessary to monitor current trends in island and river development.

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