COUNTY OF HUMBOLDT EXTRACTION REVIEW TEAM (CHERT)
HISTORICAL ANALYSES OF THE MAD RIVER: 1993-2003

Prepared by:

Andre Lehre, Bill Trush, Randy Klein, Doug Jager
County of Humboldt Extraction Review Team (CHERT)

for the

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INTRODUCTION

This report presents a retrospective analysis of trends and conditions in the lower Mad River focusing on the 1993-2003 period. The goal of this analysis was to evaluate the response of the river to gravel mining and other factors since the inception of the adaptive management program in 1992. Since 1992, the County of Humboldt Extraction Review Team (CHERT) has provided annual and multi-year reviews of gravel mining operations and river conditions. Also since that time, gravel mining companies have collected a substantial amount of monitoring information, primarily channel cross sections and air photos. The accumulated data set provided a good basis for evaluating how the river has responded to the adaptive management program and re-evaluating sustainable mining volumes and methods.

Three separate but complementary sections are included: 1) an analysis of changes in active channel width and bank erosion for the 1993-2003 period; 2) an analysis of channel cross sections evaluating changes in channel bed elevation, thalweg elevation, stored sediment, and the role of gravel mining; and 3) an evaluation of long-term changes in macro-habitat for fish to place existing conditions in an historical context.

Background

CHERT consists of four river scientists that were appointed by the Humboldt County Board of Supervisors in 1992 to provide the County with science-based management of gravel extraction. In 1998, as part of our annual post extraction report describing the 1997 mining season, we analyzed Mad River cross section data and air photos spanning the first five years of the adaptive management program (1993-97). A primary conclusion from this analysis was:

> *The bed elevations in the lower Mad River have not changed appreciably over the past six years, as documented by analysis of cross section surveys. This is consistent with an updated sediment balance for the river presented in this report, which indicates that gravel inputs to the lower river (from upstream transport and within-reach bank erosion) are in approximate balance with commercial extraction. This suggests that sustained yield for the Mad River may be somewhat lower than previously estimated by Lehre (1993).* [County of Humboldt Extraction Review Team (CHERT) 1997 Post-extraction Report with Historical Analysis for the Mad River (February, 1998)]

In the 2003 mining season, the US Army Corps of Engineers (Corps) applied a set of new terms and conditions to gravel mining operations in their Letter of Permission (LOP) based on a Biological Opinion (BO) from NOAA-Fisheries. The primary changes to mining operations were limits on annual mining volumes for the main mining reaches on Humboldt County rivers and an emphasis on 'alternative' mining methods rather than on traditional bar skimming methods. These changes arguably had the greatest impact on operations in the lower Mad River, where a volume ceiling of 150,000 cubic yards (cy) was imposed. The volume ceiling was based on an analysis performed in 2002 by the Corps (Knuuti and McComas, 2003), which compared cross sections survey in 1971 and 2000. This represented a substantial volume reduction from the average annual extraction volume of 173,000 cy for the 1992-2002 period, and a far greater reduction relative to some higher extraction years during that period (year-to-year extraction volumes can vary quite a bit, depending on how much replenishment results from winter stormflows). The analysis presented herein was conducted primarily to examine how the Mad River has responded to the CHERT adaptive management program and re-evaluate sustainable mining volume using the substantial data accumulated since its inception.

Previous Work

In 1994, a programmatic environmental impact report (PEIR) was adopted by the Humboldt County Board of Supervisors that formally established the CHERT adaptive management program for gravel mining on the lower Mad River. It enabled a mining management and resource protection plan with the following objectives (among others):

- "to obtain a degree of dynamic equilibrium and channel stability in the lower Mad River channel and to assure that changes in dynamic equilibrium and channel stability resulting from gravel mining are minimized" and
- "to safeguard fishery habitat and reduce any adverse aggregate mining-related cumulative or future impacts to a level of insignificance." (Mad River PEIR, p. 193).

The PEIR was supported by a technical analysis of historical mining and its effects on river habitat, geomorphology, and infrastructure (PEIR on Gravel Mining from the Lower Mad River; Volume II Appendices). The 1993 technical analysis included a sediment budget and sustained yield estimate that has played a major role in mining plan reviews. More recently, two additional sediment budget/sustained yield studies have been completed: one by Kondolf and Lutrick (2000) and another by Knuuti and McComas (2003) (described below). Thus there are now three 'competing' sediment budgets that address sustainable mining volumes on the Mad River which differ in how 'available gravel' is defined and in the approaches taken to determine channel changes, gravel recruitment, and sustainable mining volume. Although the sustained yield estimates from these studies are considered fairly close from a scientific perspective given the various methods used and assumptions made, the differences are considered economically significant by mine operators.

The Kondolf and Lutrick (2000) study was commissioned by Eureka Ready Mix, a Mad River gravel operator. The Knuuti and McComas (2003) report was done in-house by the US Army Corps of Engineers (Corps). Both relied primarily on Corps cross sections surveyed at two points in time: 1970 and 1999 for the Kondolf and Lutrick study and 1970 and 2000 for the Knuuti and McComas study. Lehre (1993) relied on a different set of cross sections (from Caltrans, Humboldt County, and the Humboldt Bay Municipal Water District) that spanned the period of 1929 through 1992; some cross sections also were surveyed on several occasions during the intervening period. The Corps cross sections, although more complete in their coverage of the lower river, only provided information on the net change over the thirty-year period between surveys, a serious limitation on assessing the effects of historical mining and determining scientifically-defensible limits on contemporary mining volumes.

Alternatively, the cross sections used by Lehre (1993) for the PEIR analysis, though some were surveyed several times during the period encompassed by his analysis, were spotty within the reach, leaving lengthy sections of the river with little or no survey data for some periods. The ideal data set would consist of frequent surveying of the Corps cross sections (and perhaps others) from 1970 through the present, but the actual data set is not nearly so complete. If such a data set did exist, then both spatial and temporal coverage would be sufficient to support a long term analysis that could better define the magnitude and timing of channel changes throughout the mining reach, their relationship to historical mining, and the level of sustainable harvest.

Of particular interest is the response of the river to the change in management that occurred in 1992, when the CHERT program began. This program, which continues today, brought scientifically-based mining reviews and imposed volume limits into the annual permitting process with the objective of balancing channel and habitat recovery from earlier extraction with a commercially-viable level of gravel extraction. It also initiated a comprehensive monitoring program, including a relatively dense network of annually-surveyed cross sections (and standards for data collection and presentation) and annual air photos. This data set is capable of supporting a more detailed (both in time and space) analysis of the river's conditions and trends than previously possible for refining sustainable mining volumes.

In the CHERT 1997 post-extraction report (Klein and others, 1998), we analyzed channel bed and bank changes, estimated bedload recruitment, and assessed the effects of mining for the first five years of the CHERT program (1993-1997). This analysis (now seven years old) determined that the active channel bed elevation of the river had risen modestly (roughly 0.20 feet averaged over the mining reach) during the five-year period, suggesting that reduced mining volumes (relative to prior decades) had reversed the trend of bed lowering documented in the PEIR technical analyses. At present, the cross section density in both space and time, including the considerable range in hydrologic conditions since 1993, provides a data set capable of refining sustainable mining volume. While not another complete sediment budget, this analysis is more narrowly focussed on refining the average annual sustainable mining volume for the Mad River and avoids the need to estimate recruitment for constructing a complete sediment budget.

The 2003 NOAA-Fisheries biological opinion and mitigations placed additional constraints on gravel mining in the Mad River. The most controversial constraint was a reduced cap on total mining volume (150,000 cy) based primarily on the US Army Corps of Engineers sediment budget and sustainable yield estimate (Knuuti and McComas, 2003) along with the Mad River PEIR estimate (Lehre, 1993). As mentioned above, the Knuuti and McComas study relied on cross sections surveyed in 1970 and 2000, thus (as with the Kondolf and Lutrick study) was incapable of evaluating changes that have occurred during the CHERT program. The Lehre (1993) analysis considers a more frequent time step, but was done prior to the availability of the spatially dense cross section surveys performed by the mine operators. Thus, it was determined that a new technical analysis was needed, one that uses the wealth of channel cross sections, air photos, and other information compiled since the program began in 1992. Following is a description of the methods and results of that analysis as well as conclusions describing recommended adaptations to gravel mining management based on the results.

STUDY AREA

The Mad River drains about 485 square miles and enters the Pacific Ocean in Humboldt County near Arcata, California. The basin is elongate, extending about 80 miles from the headwaters to the mouth. It lies in a region of high rates of tectonic activity (uplift and subsidence) and relatively weak rock formations. Rainfall is seasonally high, dominated by winter storms with usually only minor, but occasionally significant snowfall. Floods are typically dominated by these winter rainfall events, with rare major floods produced by rain-on-snow events, as with the '1964 flood', the largest flood of record (December 22, 1964, 81,000 cfs). Flow is regulated by Ruth Dam in the upper basin. Ruth reservoir stores only a minor volume of annual discharge, and has little effect on high discharges during the winter months. However, the dam augments summer low flows to provide municipal water supplies withdrawn from the lower river at the Humboldt Bay Municipal Water District's (HBMWD) facilities located within the gravel mining reach and to maintain required minimum flows for fish in the lower river.

Gravel mining is presently concentrated within a 7.5 mile long section in the lower river (between river mile 5.0 and 12.5; distances are relative to the mouth) (see Fig. 1). There are eight mining sites operated annually in the lower Mad River. The portion of the Mad River considered in this study naturally divides itself into an *upstream reach*, which extends from the Mad River Fish Hatchery down to the A&MRR bridge, and a *downstream reach,* which extends from the A&MRR bridge down to the O'Neill Bar, about 5000 ft below the Highway 299 bridge:

Upstream reach: In the upstream reach, the Mad River occupies a broad floodplain bounded on both sides by extensive low alluvial terraces (see Fig. 1). There are few bedrock outcrops, and the river is able to meander or braid relatively freely, except where it impinges on bank protection. A flood control levee extends from the Hatchery Road Bridge upstream along the North Fork for about 2500 feet, and downstream about 2500 ft along the right bank (RB) from the bridge to the RB endpoint of Blue Lake Bar XS 15+00. Another levee, protecting the Blue Lake treatment plant, extends along the RB from about 200 ft downstream of Blue Lake XS 38+00 to just upstream of Christie Bar XS Section 5 (CH-1) -- about 2500 ft. Finally, the revetment protecting Highway 299 forms the RB along the entire 1000-ft length of Johnson Bar between XS J-2 and XS J-4.

This upstream reach contains most of the gravel extraction sites -- Guynup, Emmerson, Blue Lake, Christie, and Johnson Bars -- and for the period 1993 - 2003 accounted for 75% of all gravel extracted on the Mad River.

Prior to floods in 1955 and 1965, this upstream reach was dominated by large meanders (Tolhurst, 1995). Following the 1965 floods, in which substantial bank erosion and filling occurred, the meanders were largely effaced and replaced by braids. Over the past 40 years the channel in this reach has been re-establishing its meandering pattern. This has been accompanied by substantial bank erosion.

Downstream reach: Between the A&MRR and the Highway 299 bridge (see Fig. 1), the Mad River lies mostly in a relatively narrow gorge incised into bedrock. Floodplain width is severely limited, and narrow alluvial terraces are discontinuously present along the banks. Bedrock outcroppings in bed and banks are common. Channel migration is limited to a narrow zone in the channel bottom, and meanders are relatively stable. Gravel extraction in this reach is limited to a small volume at Essex Bar; the remainder belongs to the HBMWD and no extraction is permitted.

Downstream from the Highway 299 bridge, the gorge widens and shallows, and a somewhat wider floodplain is present. Gravel-covered strath terraces are present fairly high (10 - 40 ft) above the channel on both banks. Bedrock outcrops are common in and along the banks. Most the gravel extraction in the downstream reach occurs here, at Johnson-Spini, Miller-Almquist, and O'Neill bars. They produced 23% of the gravel extracted from the Mad River in the period 1993-2003.

The bedrock-controlled banks again create a relatively stable channel. Forced meanders at the Johnson-Spini, Miller-Almquist, and O'Neill sites create bars which consistently replenish.

METHODS

Data Used and Preparation Methods

We quantified geomorphic changes by using the extensive cross section and air photo data set and explored possible relationships to gravel extraction by comparing geomorphic changes with gravel extraction volumes reported by the operators. For determining active channel areas and widths as well as distances between cross sections, we used annual photo montages prepared by Mr. Robert Brown of Streamline Planning Consultants for the 1992-2003 period analyzed. These photo montages were assembled using individual aerial photos from annual flights along the river corridor and arranged to approximately align with permanent ground features included in the mid-Humboldt County topographic mapping project. While these were not distortion-free, they minimized large-scale distortion and were consistent from year-to-year. The photos were printed at an approximate scale of 1:12,000 (I inch = 1,000 feet) and all measurements from these photos were scaled using this ratio. By comparing channel features shown on the cross sections with the same features shown on the air photos, a more accurate scale of 1' = 1061' was determined and this scale was used for all measurements made on the air photos.

Analysis of stored sediment volume and cross sectional changes relied on 671 individual cross-section surveys provided by Mad River gravel operators and the HBMWD at 71 locations on the Mad River over the 1993-2003 period. Only 35, or about one half, of the monitoring sites span the entire 11-year period, and of these only 28 have complete yearly records. Table 1 lists the sites, their river locations, and their periods of record. The surveys were provided to CHERT by the operators or their consultants, and by HBMWD. Appendix I contains plots of each cross-section at three times -- 1993 (or earliest post-1993 available), 1997, and 2003 (or latest pre-2003 available). All cross-sections are plotted to the same scale.

Monitoring cross-sections were surveyed each year in late Spring or early Summer, prior to gravel extraction, and, if extraction affected them, again in Fall after extraction was complete. In this analysis we use only the pre-extraction (Spring) cross-sections.

The detail and completeness of the cross-section surveys are quite variable in both space and time, partly because monitoring requirements have changed over time, partly because of changes in surveying techniques, and partly because of differences in the approaches of individual surveyors. In general, more recent surveys are superior to the earlier ones. Substantial effort was required to make the cross-sections consistent and comparable.

The main problems encountered in the surveys were:

1) loss of one or both endpoints due to bank erosion (in some XSS this happened repeatedly), requiring adjustment of XS distances to make the XSS of different years comparable, and introducing uncertainty in XS alignment;
2) incomplete survey between endpoints (e.g., survey of only the near-channel or extracted area, and not of the entire width) requiring part of the XS to be estimated using data from surveys in adjacent years;
3) inconsistent geodetic datum between surveys and sites -- all surveys had to be adjusted to the NAVD88 datum;
4) inconsistent detail between yearly surveys (e.g., in one year the entire width is surveyed in great detail, and in a subsequent year only one-half or one-third as many points are taken) introducing additional error in comparing years;
5) omission of survey of thalweg or deeper parts of the channel in Spring (presumably because of water depth) -- we inserted thalweg data from the Fall survey if available;
6) missing years at XSS;
7) abandonment of a XS or XS realignment (e.g., due to shifting of the channel) without at least one year of overlap with its replacement; and
8) errors in survey distances or elevations discovered when comparing surveys of adjacent years. (These were adjusted by eye to make the aberrant XS consistent with the XSS of the previous and succeeding years.)

The geomorphic analysis of the cross-sections focused on five quantities that could be determined from them for each year:

1) mean elevation of XS below a specified reference level
2) elevation of thalweg (deepest point in river) in XS
3) width of XS at the reference level
4) area of XS below reference level
5) volume change between adjacent XSS

In addition, the number of years that each cross-section experienced extraction was tabulated.

Table 1 -- Cross-Sections Used in Analysis

Cross-sections are listed in order from upstream to downstream. Distances upstream provided by R. Brown. Streamline Planning Consultants, except for those marked *, which are estimated from R. Klein's channel CL(centerline) measurements. Reference elevation is that used in computation of channel mean elevation and cross-sectional area.

XSS upstream of A&MRR Bridge

Site	XS	Distance Upstream, ft	XS Reference Elevation, ft	Period Spanned	Years Missing in Period	No. of Years with XSS
Guynup Bar	1	55,373	96.0	1993 - 2003	none	11
	2	54,923	96.0	1993 - 2003	none	11
	3	54,593	94.0	1993 - 2003	none	11
	4	54,213	93.0	1993 - 2003	none	11
	5	53,863	91.0	1993 - 2003	none	11
	6	53,563	90.0	1993 - 2003	none	11
	7	53,138	90.0	1993 - 2003	none	11
	8	52,588	88.5	1993 - 2003	none	11
Emmerson Bar	30+00	52,293	89.0	1994 - 2003	2003	9
	27+00	52,033	88.0	1994 - 2003	none	10
	23+00	51,693	85.0	1994 - 2003	none	10
	18+38	51,308	85.0	1994 - 2003	none	10
	15+00	50,938	85.5	1994 - 2003	none	10
	11+00	50,738	85.0	1994 - 2003	none	10
	6+00	50,263	82.0	1994 - 2003	none	10
	1+00	49,790	78.0	1994 - 2003	none	10
Blue Lake Bar	Disk 1	49,110	76.0	1995 - 2003	none	9
	Disk 2	48,835	80.0	1995 - 2003	none	9
	0+00	48,510	80.0	1993 - 2003	none	11
	5+00	48,073	80.0	1993 - 2003	none	11
	10+00	47,623	80.0	1993 - 2003	none	11
	15+00	47,223	80.0	1993 - 2003	none	11
	20+00	46,523	75.0	1993 - 2003	none	11
	25+00	45,893	75.0	1993 - 2003	none	11
	30+00	45,503	74.0	1993 - 2003	none	11
	34+00	45,103	73.0	1993 - 2003	none	11
	38+00	44,603	70.0	1993 - 2003	none	11
	42+00	44,153	71.0	1993 - 2003	none	11
Christie Bar	Section 5 (CH1)	42,997	64.0	1995 - 2003	none	9
	Radial 4	42,647	64.0	1995 - 2003	2002	8
	Radial 3 (CH2)	42,347	64.0	1995 - 2003	none	9
	Radial 2	41,872	63.5	1995 - 2003	2002	8
	CH3	41,400*	62.0	2002 - 2003	none	2
	Radial 1	41,422	63.0	1995 - 1999	none	5
	22+87	40,997	60.0	1993 - 2003	2002	10
	21+64 (CH4)	40,547	60.0	1993 - 2003	none	11
	17+47	40,147	59.0	1993 - 2001	none	9
	CH5	39,734*	58.0	2002 - 2003	none	2
	13+33	39,447	58.0	1993 - 2001	none	9
	9+99	39,147	56.0	1994 - 2001	none	8
	CH6	38,991*	54.0	2002 - 2003	none	2
	6+66	38,797	55.5	1993 - 2001	none	9
	3+33 (CH7)	38,447	55.5	1994 - 2003	none	10
	0+00 (CH8)	38,047	54.0	1993 -2003	none	11
Johnson Bar	J-1 (CH-9)	37,597	50.0	1996 - 2003	none	8
	J-2	37,047	50.0	1996 - 2003	none	8
	J-3	36,497	47.0	1996 - 2003	none	8
	J-4	36,167	45.0	1997 - 2003	none	7

continued

Table 1 -- Cross-Sections Used in Analysis (continued)

XSS downstream of A&MRR Bridge

Site	XS	Distance Upstream, ft	Reference Elevation, ft	Period Spanned	Years Missing in Period	No. of Years with XSS
HBMWD upper	8	30,858	48.5	1992 - 2003	1998, 1999, 2000	9
	7	29,553	44.0	1992 - 2003	1998, 2000	10
	6	28,596	39.0	1992 - 2003	1998, 2000	10
Essex Bar	1	28,304	38.0	1993 - 2003	none	11
	2	27,979	39.0	1993 - 2003	none	11
	3	27,629	44.0	1993 - 2003	none	11
HBMWD lower	5	27,030	40.0	1992 - 2003	1998, 2000	10
	4	25,725	35.5	1994 - 2003	1998, 2000	8
	3	24,681	28.0	1992 - 2003	1998, 2000	10
	2	23,724	31.0	1992 - 2003	1998, 2000	10
	1	22,941	26.0	1992 - 2003	1998, 2000	10
Johnson-Spini Bar	1	21,081	25.0	1990 - 2003	1992	13
	2	20,756	27.5	1991 - 2003	1992	13
	3	20,366	27.5	1990 - 2003	1992	13
	4†	19,886	28.0	1990 - 2003	1992	13
Miller-Almquist Bar	5	19,506	25.0	1994 - 2003	none	10
	6	19,170	23.0	1994 - 2003	none	10
	7	18,760	20.0	1994 - 2003	none	10
O'Neill Bar	8	17,780	17.0	1995 - 2003	none	9
	9	17,480	18.0	1995 - 2003	none	9
	10	17,180	18.0	1995 - 2003	none	9
	11	16,880	20.0	1995 - 2003	none	9
	12	16,580	18.5	1995 - 2003	none	9

† According to Aldaron Laird, agent for Miller Farms, this cross-section should be included as part of the Miller-Almquist site. However as it spans the both the downstream end of the Johnson-Spini right bank bar and the upstream end Miller-Almquist left bank bar (formerly referred to as the Johnson-Spini left bank bar) we have chosen to leave it as the data was originally supplied to us.

Of particular interest are the yearly changes in cross-sectional mean elevation, width, area, and volume, and in thalweg elevation, and whether they show any consistent trends with time, streamwise distance, or number of years with extraction.

Active Channel Widths and Areas

Active channel widths and surface areas were needed both for evaluating changes in the active channel as a measure of channel stability and for estimating sediment storage volume changes through time. We defined the active channel at that portion of the river corridor with relatively frequent (at least once every several years) sediment deposition or scour, a measurement relatively easily obtained from plots of sequential survey data for each cross section. Where active channel limits were unclear on cross sections, air photos were examined to assist in delineation. Air photos might also have been used alone for this task, but issues of imprecise scale and distortion would have reduced the accuracy of the measurements.

Active channel area was derived for polygons defined between adjacent cross sections along the river. To estimate active channel area, the average of two adjacent active channel widths was multiplied by the distance between the cross sections as measured along the active channel centerline. Here, we had to use the air photos for active channel centerline distances.

As a check on the accuracy of this technique, the areas of several polygons were also measured using a planimeter on the air photos. To minimize errors, only areas within the central (most distortion-free) portions of a photo were used for this comparison, and a local scale was calculated by comparing the active channel widths for several cross sections using both the cross section plots and the air photo. Three polygons of different size, all irregularly shaped, were chosen to provide a worst-case scenario. In two of the three cases, the areas calculated using cross section and channel centerline distances were larger than those using the planimeter on the air photo (0%, 4%, and 1%), with a mean difference 2%. This was not considered too great a difference for the purposes of this study.

Certainly, a superior method would be to use more high-tech resources and methods (e.g., a digital ortho-rectified air photo and GPS-derived coordinates) for active channel areas, but these were not available for this study.

Bank Erosion

Bank erosion was determined for 1998 through 2003 using a combination of measurements from cross sections and air photos. Because of the small scale and distortion associated with the air photos, they were only used to determine the lengths of bank erosion polygons. Widths and heights of bank erosion were determined from the cross sections, with cross sectional area of bank erosion calculated as the product of width and height. For width, the average of top width and bottom width was used. In some cases, the cross section was oblique to the long axis of the feature. For these cases, the cross sectional area determined from the cross section was reduced by multiplying the area by the cosine of the angle off perpendicular to the long axis (Fig. 2).

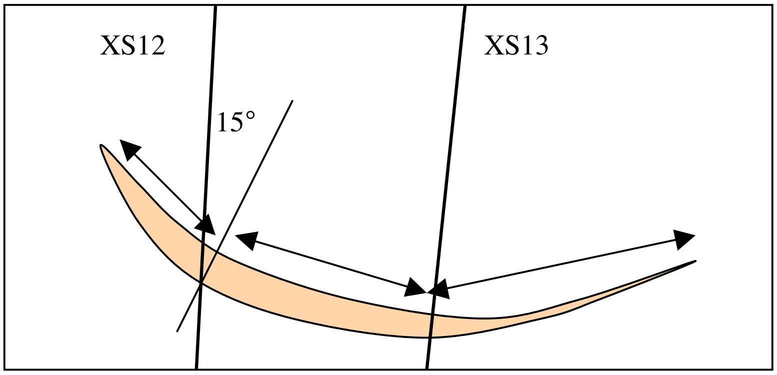

Fig. 2 Definition sketch for adjusting XS area for bank erosion estimates at non-perpendicular XS: adjusted area of XS12 with bank erosion = (XS12 area of bank erosion) x (cosine of angle). XS 13 area OK without adjustment.

Where two cross sections intersected a particular bank erosion feature, the eroded areas (adjusted if necessary) were averaged and this was multiplied by the intervening horizontal distance to get a volume of bank loss between the cross sections (double-end-area formula). The volume of bank erosion extending upstream and/or downstream of a cross section was calculated as the erosion area at the cross section divided by 2 and multiplied by the length between the cross section and the ending distance as determined from the air photo. This same formula was also used where only one cross section intersected a bank erosion feature for calculating the volumes upstream and downstream of the cross section. Careful review of sequential air photos indicated that all detectable bank erosion features were intersected by at least one cross section.

Bank erosion volumes were calculated individually for each feature, and are reported here as sums for each mining site by each year. Where a bank erosion feature overlapped on two adjacent sites, it was included with the site having the greatest proportion of the volume.

Data Extraction Procedure

Data extraction from each cross-section involved six steps:

1) **Estimation of ground-surface elevations at 1-foot intervals:** Ground-surface elevations were estimated at 1-foot intervals across the width of the cross-section by linear interpolation of elevations between adjacent survey points using the Excel macro Lintrp 1.4 (developed by A. Lehre and available from the Humboldt State University website). The closer the spacing of survey points, the better the elevation estimates.

2) **Selection of reference elevation:** For each cross-section, a *reference elevation* was selected by overlaying the XSS for all years on the same graph and choosing an elevation below which lay all significant yearly flow or man-caused changes in bed, bars, and banks. The reference elevation controls which data points are used in computation of mean elevation and cross-sectional area (see Fig. 3 below).

3) **Measurement of XS width:** For each year the width of the cross-section *at the reference elevation* (Fig. 3) is determined by inspection of the interpolated elevation values. The ends of the reference line are chosen at those distances whose elevations most closely correspond to the reference elevation. (In the case of bank topography that extends above, and then drops below the reference elevation, the most streamward distance was usually chosen.) Uncertainties in the position of endpoint elevations estimated by interpolation cause corresponding uncertainties in estimation of XS width. The greatest uncertainties occur where banks are gently sloping; small differences in elevation there are accompanied by considerable changes in width. As the banks at or near the reference elevation become steeper, width estimates become more reliable. Thus differences in XS width of less than 5 to 10 feet are generally not meaningful; they may simply reflect interpolation error rather than real changes.

4) **Computation of mean elevation of XS:** Mean elevation of the cross-section in each year is computed as the *average* of all the interpolated points included between the right and left ends of the reference elevation line. The endpoint elevations are included in this average, even if they lie above the reference elevation value.

5) **Computation of XS area:** Computation of the cross-sectional area lying between the reference elevation and the ground surface is a two-step process (Fig. 3). First, the area between the reference elevation and sea level is computed by multiplying the XS width by the reference elevation. Second, the *sum* of all the interpolated points included between the right and left ends of the reference elevation line yields the area of the cross-section lying between the ground surface and sea level. Subtracting these two areas gives the area of the cross-section lying between the reference elevation and the ground surface.

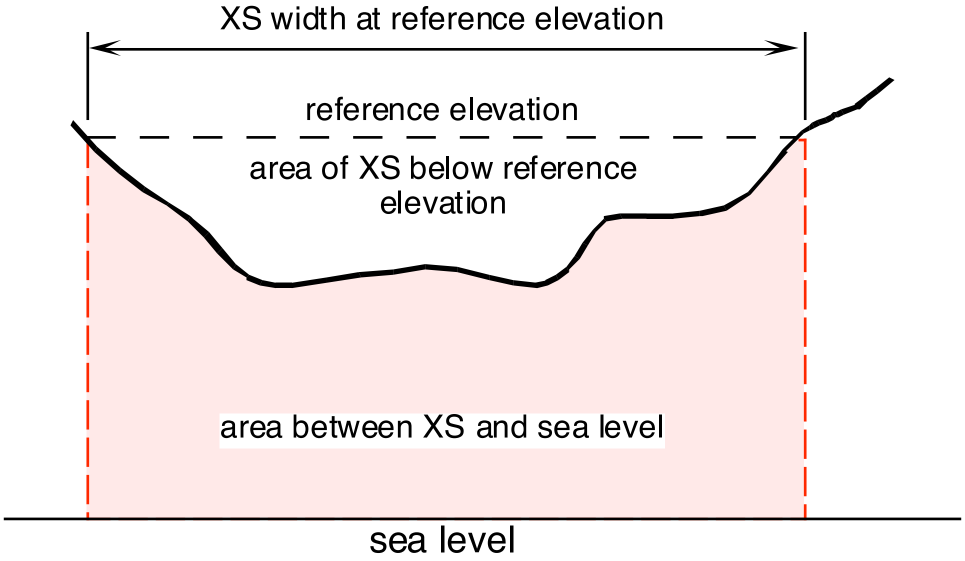

Fig. 3 Definition sketch for determination of XS area and mean elevation

area of XS below reference elevation =
(XS width at reference elevation) x (reference elevation) – (area between XS and sea level)

6) **Determination of thalweg elevation:** Thalweg elevation is taken as the minimum elevation in the channel portion of the cross-section. Off-channel excavations (terrace trenches or wetland pits) are excluded since they are not part of the channel, even though they may contain the minimum elevation in the XS.

The resulting data were tabulated by year for each cross-section and are available electronically in the Excel spreadsheet *Mad R XSS Data Summary 2003*.

Mean Elevation, Thalweg Elevation, and Channel Confinement

Mean elevation: The *mean elevation* of a cross-section is the arithmetic average of all the interpolated elevation points lying between the ends of the reference elevation line (see Fig. 3). This includes all parts of the cross section which have undergone significant elevation changes, due either to stream processes or to gravel extraction. Thus it encompasses not only the low-water and active-channel areas, but also those parts of the floodplain and lower terraces that have experienced erosion, deposition, or extraction.

Changes in mean elevation reflect the *overall* behavior of the cross-section and can *suggest* whether the channel is experiencing net downcutting (*degradation*) or filling (*aggradation*). It does not, however, indicate whether the deeper parts of the channel (e.g., the thalweg) are aggrading or degrading. In addition, if the channel experiences significant widening through bank erosion, the mean elevation can increase even though the channel has experienced a net loss of material. Fig. 4. schematically illustrates this. Only when cross-section width is essentially constant do changes in mean elevation correspond uniquely to changes in cross-sectional area

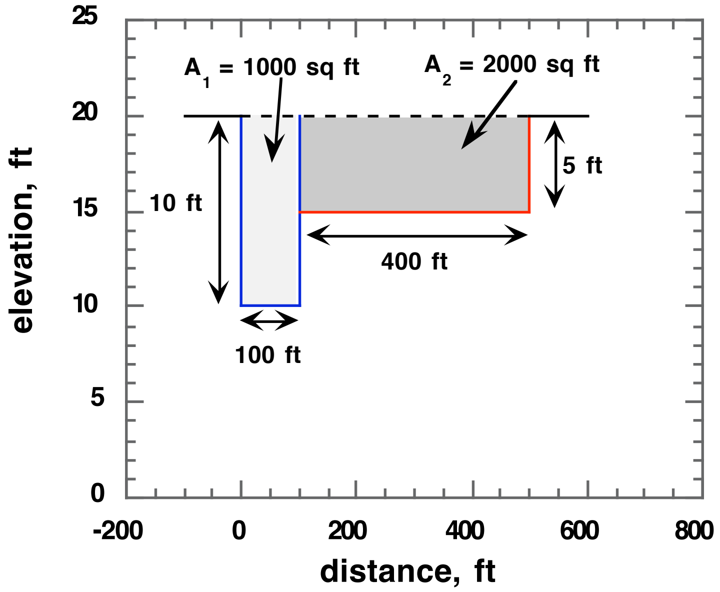

Fig. 4 Decrease in mean elevation due to channel widening

In the figure above, the channel is initially 10 ft deep and 100 ft wide. The cross-section has mean elevation z_1 = 10 ft and cross-sectional area A_1 = 1000 ft^2. Erosion on the right bank causes the channel to widen by 400 ft at an elevation of 15 ft. The new mean elevation is

$$z_2 = (10 \text{ ft} \times 100 \text{ ft} + 15 \text{ ft} \times 400 \text{ ft}) / (100 \text{ ft} + 400 \text{ ft}) = 14 \text{ ft}$$

which is greater than the original mean elevation, but the cross-section has actually *increased* in area by A_2 = 2000 ft^2. Thus an *increase* in mean elevation has been accompanied by a *net loss* of material.

Thalweg elevation: The *thalweg* is the line of maximum depth of the river. The *thalweg elevation* is thus the lowest channel-related elevation (as opposed to an off-channel or excavation-related elevation) in the cross-section.

Channel confinement: The difference between cross-section mean elevation and thalweg elevation is a measure of *channel confinement*: the greater the difference, the more confined the channel. Thalweg elevation commonly tracks mean elevation, but channel in-filling or bar surface lowering may result in diminished confinement. Conversely, bar buildup or thalweg scour may produce increased confinement.

RESULTS

Active Channel Widths and Areas

Active channel areas are shown in Figure 5 along with annual maximum peak discharges for the USGS stream gage located within the study reach (Mad River near Arcata, No. 11481000). In this graph, we have included active channel widths determined for the Mad River PEIR technical appendix (Lehre, 1993) for a longer term view. Though the methods were different for the earlier period (1954-92) and the later period (1994-2003), they are roughly comparable.

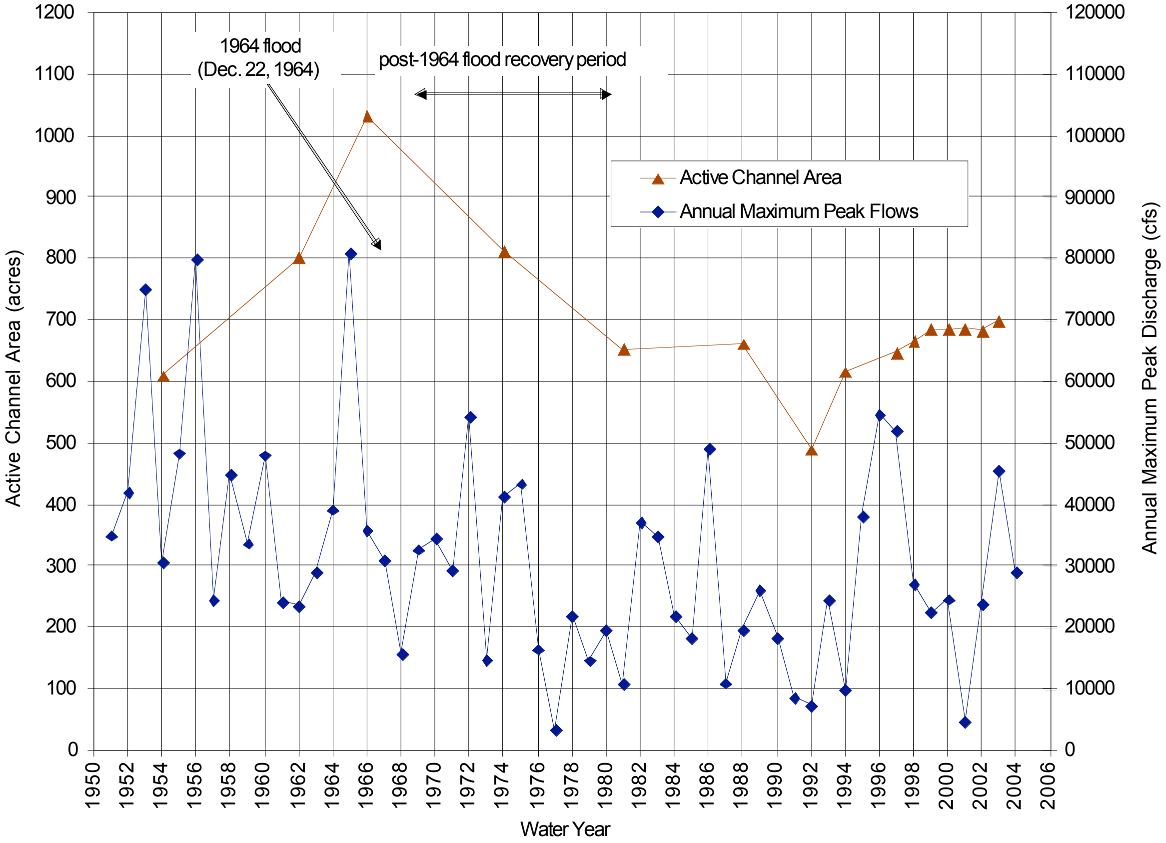

Fig. 5 Mad River peak flows and active channel areas, 1951-2003.

A relationship between active channel area and peak discharges is suggested in Figure 5. Large floods appear to widen the active channel, while extended periods with no large floods allow the channel to narrow as vegetation destroyed by the previous large flood encroaches on fresh deposits. The largest flood of record (81,000 cfs) occurred in December, 1964 (water year 1965), causing widespread destruction of previously stable floodplain and terrace surfaces, as indicated by the abrupt increase in active channel area observed in 1966 air photos used for determining active channel area for the PEIR. Over the following decade or so, the active channel shrunk back to the pre-1964 condition, and continued to shrink until the early 1980s, when it became quasi-stable. Active channel area has remained between about 600 and 700 acres since the beginning of the CHERT adaptive management program.

Interestingly, a large flood in January, 1953 (75,000 cfs) although not much smaller that the 1964 flood, appeared to have little effect on active channel area. A likely explanation for this is that the rapid logging in the basin area upstream from the study reach between these two floods generated a tremendous amount of erosion and sediment, causing the 1964 flood to have far more devastating effects than the 1953 flood. Another large flood occurred in December, 1955 (water year 1956), but active channel area was not determined from air photos taken between this flood and the 1964 flood, so the response, or lack thereof, in active channel area is undetermined for this flood.

Bank erosion volumes determined for this study are shown in Table 2.

Table 2 -- Annual bank erosion volumes by site and year for the lower Mad River, 1998-2003 (cy = cubic yards).

	Site[1]					Ann Total
Period	**MRS**	**EMM**	**BLU**	**CHR**	**JOH**	**(cy)**
1997-98	16,812	19,842	19,729	12,953	1,913	71,249
1998-99	2,046	93	25,597	10,808	16,228	54,772
1999-00	0	1,546	16,059	11,564	11,250	40,419
2000-01	0	74	0	1,788	298	2,160
2001-02	7,856	1,822	8,768	14,849	4,875	38,170
2002-03	47,920	10,584	88,376	49,178	28,322	224,380
Site Total	**74,634**	**33,961**	**158,529**	**101,140**	**62,886**	**431,150**

[1] Site codes are as follows: MRS is Mad River Sand and Gravel; EMM is Emmerson Bar; BLU is Blue Lake Bar; CHR is Christie Bar; JOH is Johnson Bar

As mentioned earlier, we also calculated bank erosion volumes for the 1993-97 period in our 1997 post-extraction report. These, along with the annual totals from Table 1, are shown below in Table 3 for the study reach as a whole.

Table 3 -- Annual bank erosion volumes and peak discharges for the lower Mad River, 1993-2003.

Period	Bank Erosion (cy)	Annual Peak Q (cfs)
1992-93	7,000	24,500
1993-94	2,000	9,840
1994-95	211,000	38,100
1995-96	61,000	54,700
1996-97	370,000	51,900
1997-98	71,249	27,100
1998-99	55,000	22,400
1999-00	40,000	24,600
2000-01	2,000	4,790
2001-02	38,000	23,900
2002-03	224,000	45,500
Total	**1,081,249**	**---**

Figure 6 shows these data in graphical form. As expected, and as with active channel area, bank erosion appears strongly dependent on floods. An exception is seen following the relatively large flood in 1996, when bank erosion was relatively small compared to other large floods in 1995, 1997, and 2003. We cannot explain this phenomenon, other than to suggest that the previous year (1995) was the first large flood for several years, causing a large volume of bank erosion. Perhaps the 1995 flood had ‘reset’ the channel, removing most of the unstable banks, leaving little remaining for the 1996 flood the very next year. Flood flow duration, which was not examined here, may also explain some of this disparity.

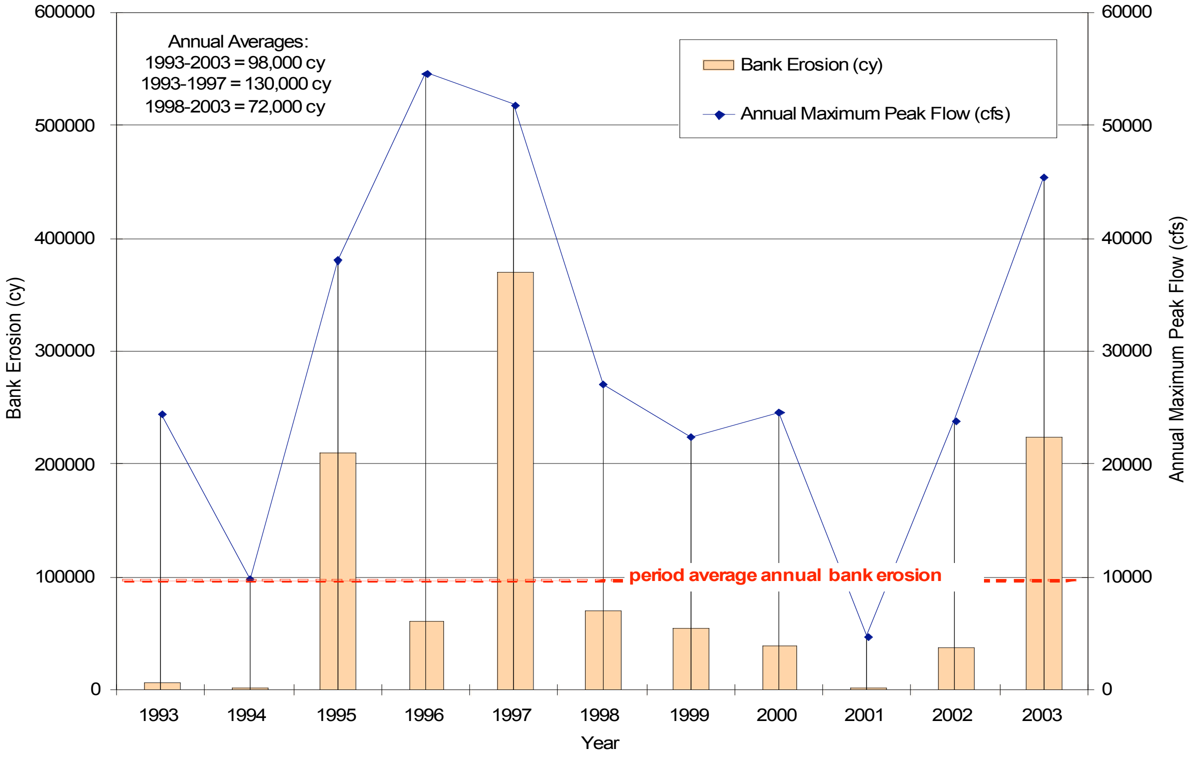

Fig. 6. Bank erosion and peak discharges in the lower Mad River, 1993-2003.

Temporal and Spatial Changes in Mean Elevation, Thalweg Elevation and Confinement

Temporal (time) changes: We investigated temporal changes in mean elevation, thalweg elevation, and confinement by plotting mean and thalweg elevation vs. year for each cross-section. Figures 7A and 7B are upstream and downstream examples. The complete set of 68 plots is given in Appendix A.

The plots indicate that thalweg elevation and mean elevation generally track each other, i.e., as mean elevation increases or decreases so does thalweg elevation, although not necessarily by the same amount, or in every year. Figures 7A-B illustrate this overall pattern.

The amount of channel confinement is indicated by the vertical distance between the mean and thalweg elevation lines. Confinement decreases as the lines approach each other; increasing confinement is indicated by increasing separation between the lines (see Fig. 7A).

Spatial changes : We investigated spatial changes in mean elevation, thalweg elevation, and confinement by plotting mean elevation, thalweg elevation, and confinement at each cross-section vs. streamwise distance (distance upstream from Hwy. 101) of the section. Individual plots were made for each upstream site, while the downstream sites were grouped into two composite plots. Each plot overlays the 1993 (or earliest post-93), 1997, and 2003 data, so these also permit assessment of temporal changes. It should be noted that the graphs of mean elevation and thalweg elevation are *long profiles* of the river channel. Figures 8, 9, and 10 are examples of these graphs (complete sets of plots are presented in Appendices B, C, and D).

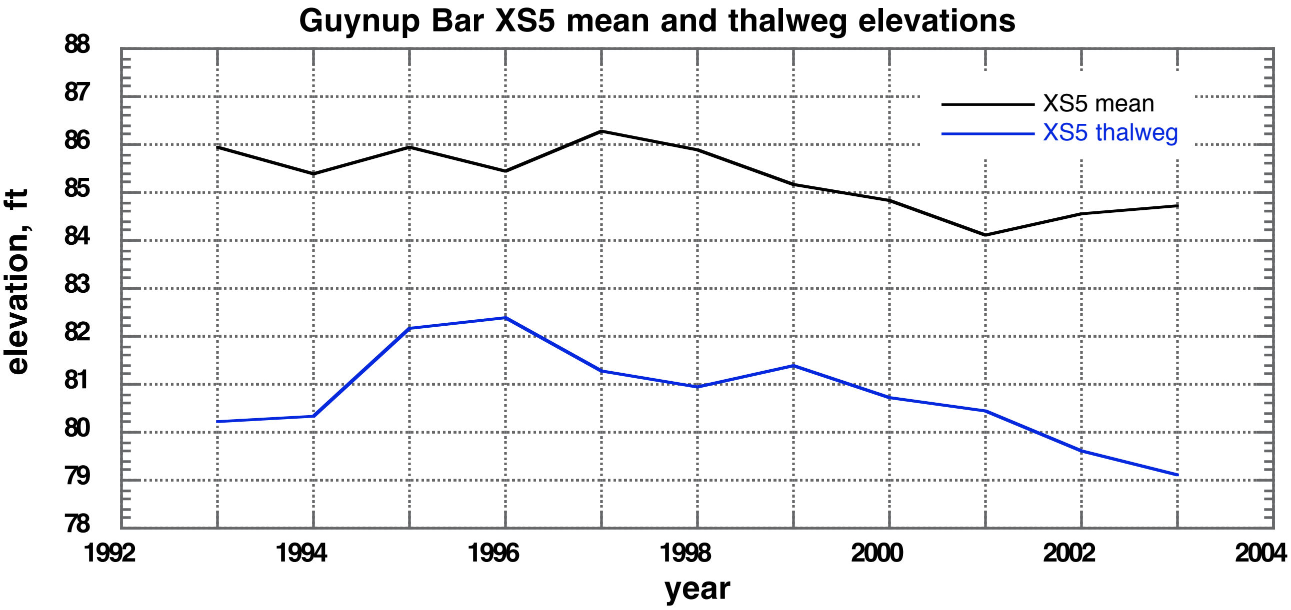

Fig. 7A Variation of mean elevation and thalweg elevation with time at Guynup XS 5.

Note in Fig. 7A the overall similarity in pattern of increases and decreases in mean and thalweg elevation at this upstream site The distance between the two lines is an indicator of channel confinement. Confinement decreased from 1994 to 1996 as thalweg elevation increased by about 2 ft while mean elevation stayed essentially constant. Since 1997 both mean and thalweg elevations have generally declined, but since 2001 confinement has increased as slight increases in mean elevation have been accompanied by a continuing lowering of the thalweg. From 1997-2003 mean elevation has declined an average of 0.30 ft/yr while the thalweg has lowered an average of 0.36 ft/yr. For the entire 1993-2003 period of the average lowering rate at this XS of both mean elevation and thalweg is about 0.15 ft/yr.

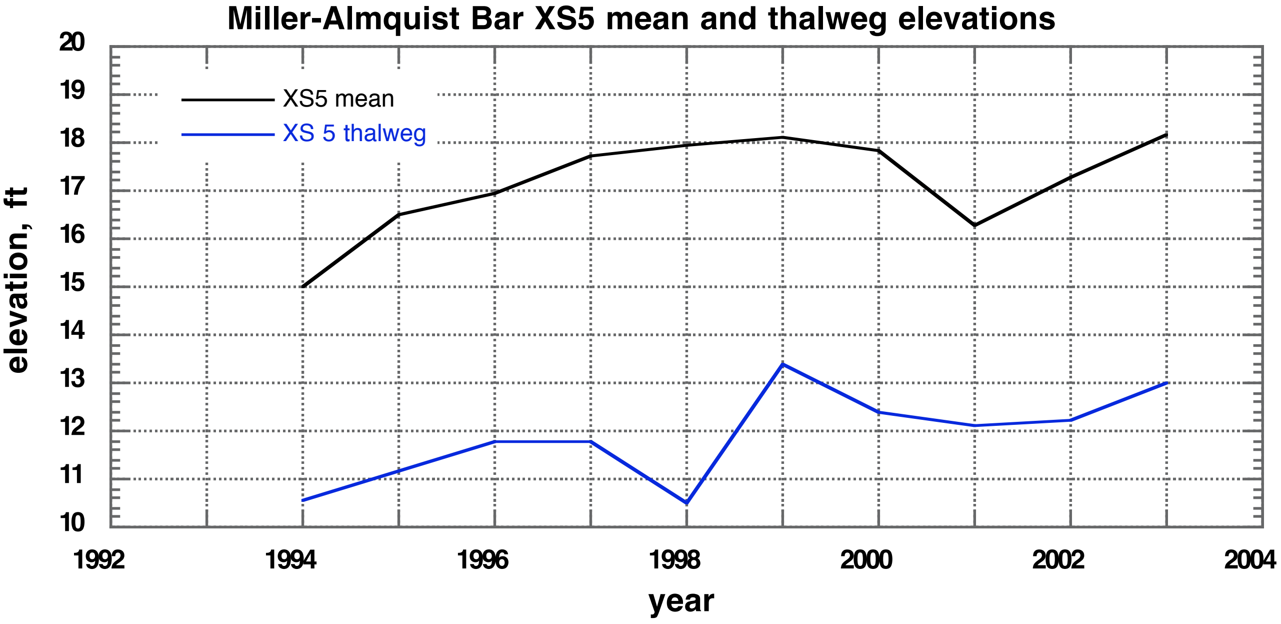

Fig. 7B Variation of mean elevation and thalweg elevation with time at Miller-Almquist XS 5.

The plot in Fig. 7B, at a typical downstream site, clearly shows generally rising bed and thalweg elevations -- note the overall similarity in pattern of the lines. With the exception of 1998, the distance between the mean and thalweg elevation lines has stayed approximately constant, indicating that channel confinement has remained nearly unchanged despite an increase in bed and thalweg elevations of nearly 3 ft since 1993. Downstream sites have mostly shown increasing bed and thalweg elevations since 1993

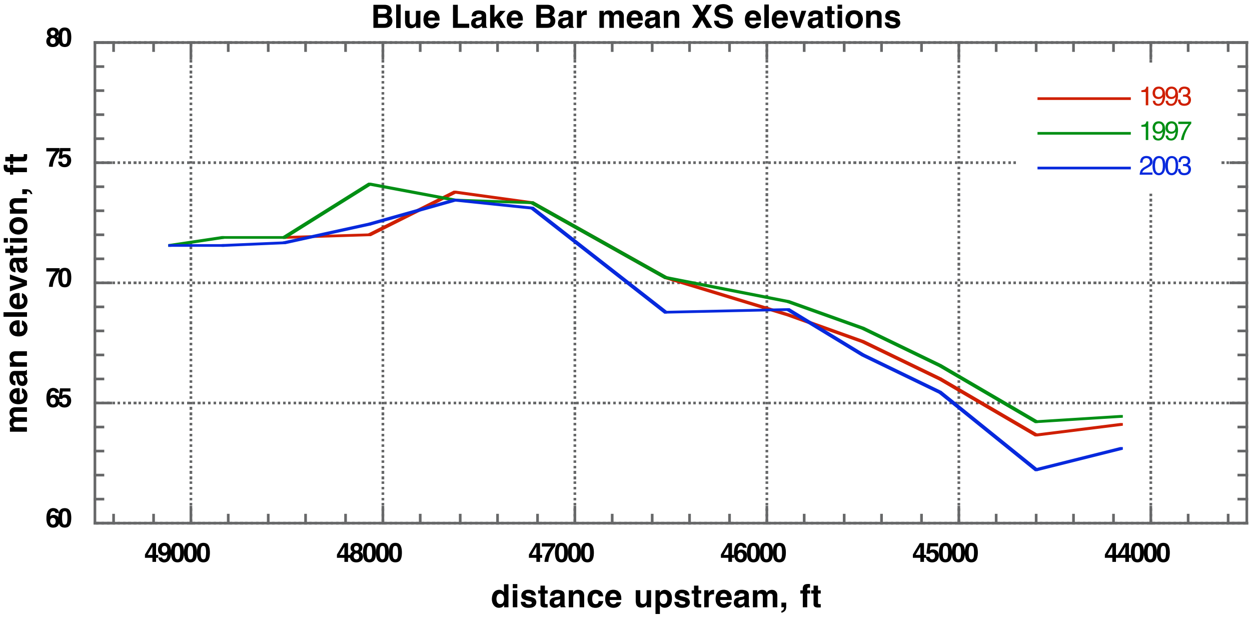

Fig. 8A Mean elevation long profiles of Mad River at Blue Lake Bar.

This plot is fairly typical of the pattern of mean elevation change seen at upstream sites. There was generally an increase of mean bed elevation between 1993 and 1997, followed by a slow consistent decline in mean elevation in the period 1997-2003. The mean elevations are now generally at or below the 1993 level.

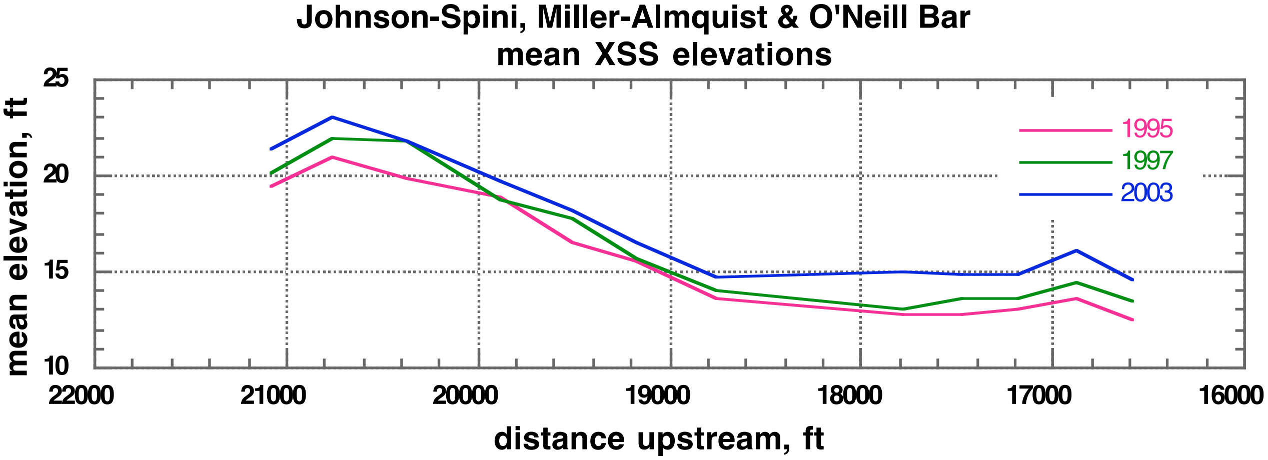

Fig. 8B Mean elevation long profiles of Mad River at Johnson-Spini, Miller-Almquist, and O’Neill bars.

This plot is typical of the pattern of mean elevation change at downstream sites. Since 1993 Mean bed elevation has consistently increased in downstream areas.

Patterns of elevation change:

Mean elevation: At upstream sites, mean bed elevation generally increased between 1993 and 1997, followed by a slow consistent decline in mean elevation in the period 1997 - 2003. Mean upstream elevations are now generally at or below the 1993 level. These trends are evident in Figs. 8A and 8A.

In the downstream reach, between 1993 and 1997 the HBMWD and Essex sites underwent a small amount of mean lowering, while a large increase in mean elevation occurred at the sites downstream of Highway 299. After 1997, all downstream sites increased in mean elevation. Figs. 8B and 8B are typical examples.

To investigate patterns of mean elevation change at individual sites, we divided the cross-sections at each of the four large upstream bars into upstream, middle, and downstream groups; the cross-sections at all the other sites were divided into either upstream or downstream groups (Table 4). The means of each group for the 1993-97 and 1997-2003 periods are given in Table 5 and plotted in Figs. 9A-C. Overall mean changes for each site are compared for the 1993-97 and 1997-2003 periods in Fig. 10.

Table 4 -- Cross-section groups used in spatial analyses

	XSS used		
Site	**upstream**	**middle**	**downstream**
Guynup Bar	1–4	5–6	7–8
Emmerson Bar	30+00 – 18+28	15+00–11+00	6+00–1+00
Blue Lake Bar	Disk1–10+00	15+00–25+00	30+00–42+00
Christie Bar	Section 5–22+87	21+64–13+33	9+99–0+00
Johnson Bar	J1–J2		J3–J4
HBMWD upper	8		7–6
Essex Bar	1		2–3
HBMWD lower	5–4		3–1
Johnson-Spini Bar	1–2		3–4
Miller-Almquist Bar	5		6–7
O'Neill Bar	8–9		10–12

Table 5 -- Spatial variation of changes in mean elevation at sites

To reduce round-off errors in summing and averaging, quantities in this table are given to more significant figures than justified; individual values should be rounded to the nearest tenth before citation or use. Negative values indicate ground lowering.

	mean elevation change 1993-1997, ft			**mean elevation change 1997-2003, ft**		
Site	**upstream**	**middle**	**downstream**	**upstream**	**middle**	**downstream**
Guynup Bar	0.98	-0.34	0.67	-0.77	-0.73	-0.35
Emmerson Bar	0.64*	-0.83*	-0.76*	-0.54*	0.08	-0.41
Blue Lake Bar	0.20*	0.23	0.53	-0.45	-0.70	-1.39
Christie Bar	0.63*	0.28*	1.22*	-1.94*	-0.16*	0.40*
Johnson Bar				-0.70		0.95
HBMWD upper	1.51		-0.90	1.17		0.33
Essex Bar	0.06		-0.31	0.49		-0.07
HBMWD lower	-0.03*		-0.39	0.35		0.35
Johnson-Spini Bar	2.98		3.86	1.23		-0.09
Miller-Almquist Bar	2.71		2.04	0.44		0.78
O'Neill Bar	0.55*		0.75*	1.57		1.34

* indicates that the value includes one or more XSS that span fewer years than the column header indicates.

Table 5 and Figs. 9A-B suggest that for the large upstream bars, the greatest changes in mean elevation tend to occur at the upstream cross-sections, with the downstream cross-sections a close second. The mid-bar cross-sections mostly show smaller changes. For the downstream sites, the cross-sections at the upstream ends generally experienced greater changes in mean elevation than those at the downstream ends (Fig. 9C).

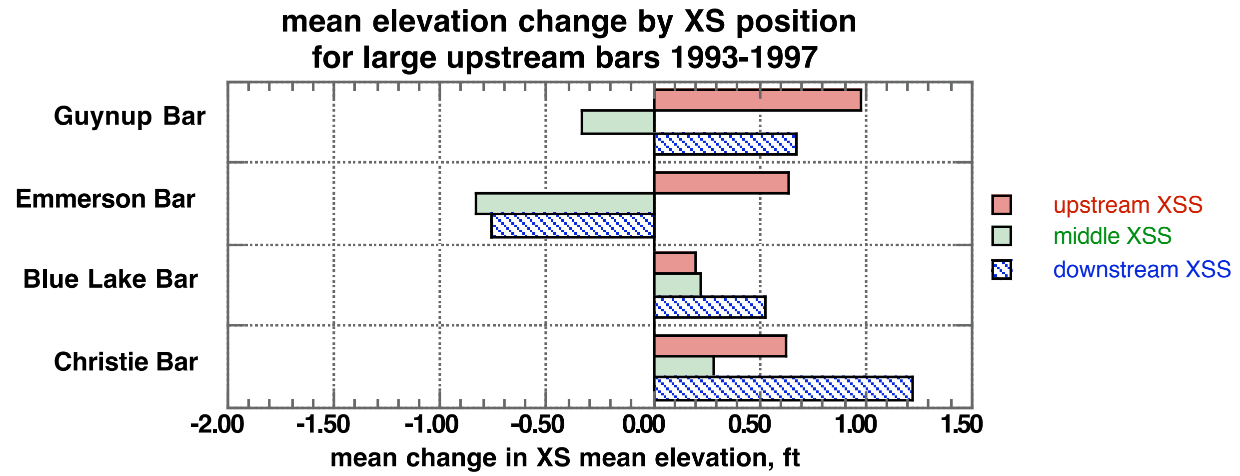

Fig. 9A Mean changes in XS mean elevation by position on bar at large upstream sites, 1993-97.

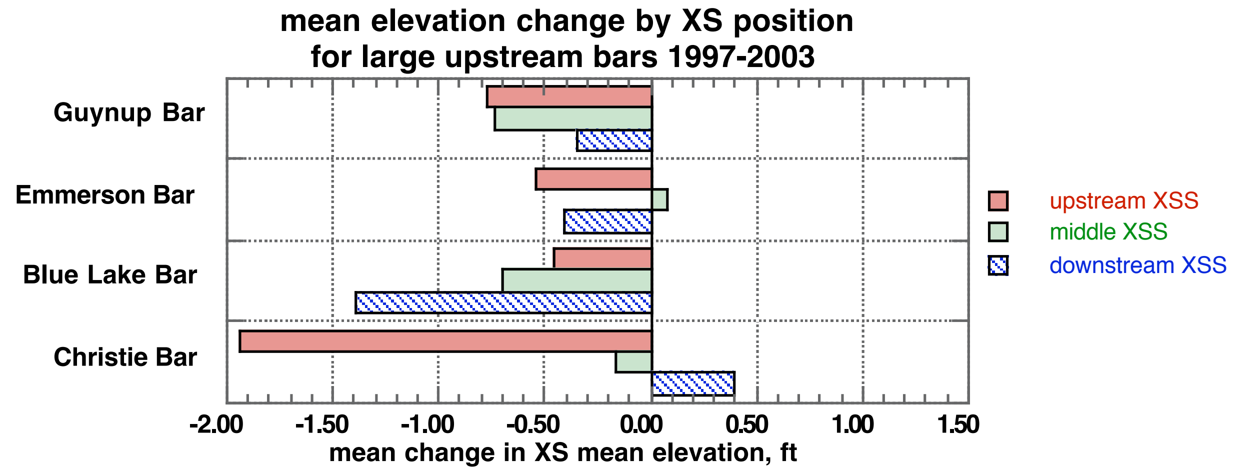

Fig. 9B. Mean changes in XS mean elevation by position on bar at large upstream sites, 1997-2003.

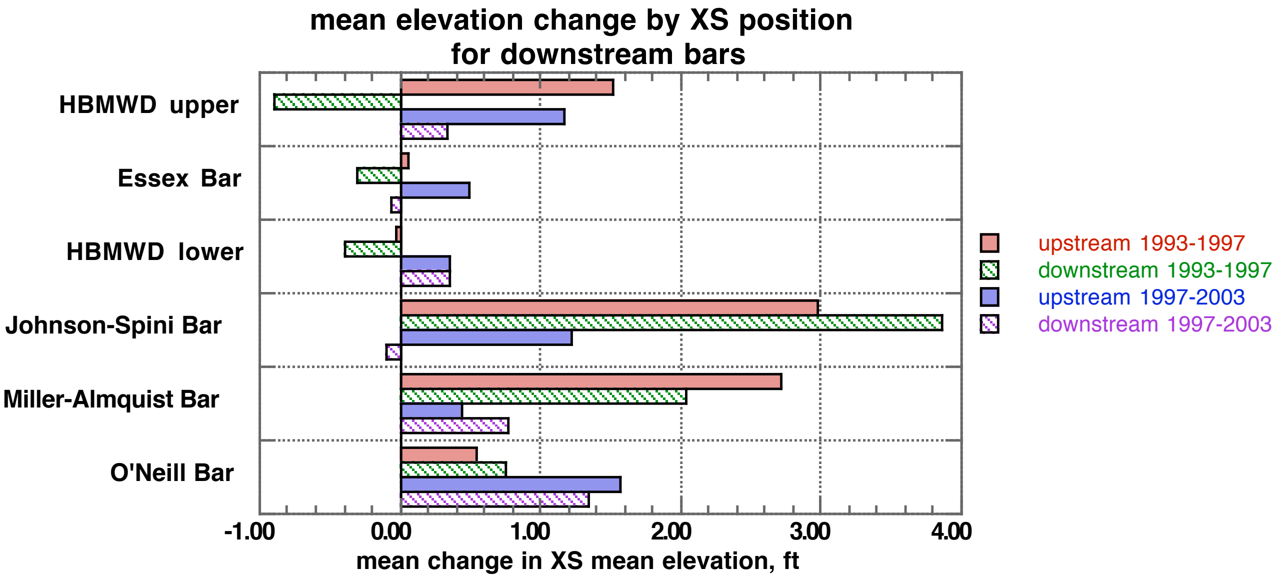

Fig. 9C . Mean changes in XS mean elevation by position on bar at downstream sites, 1993-2003.

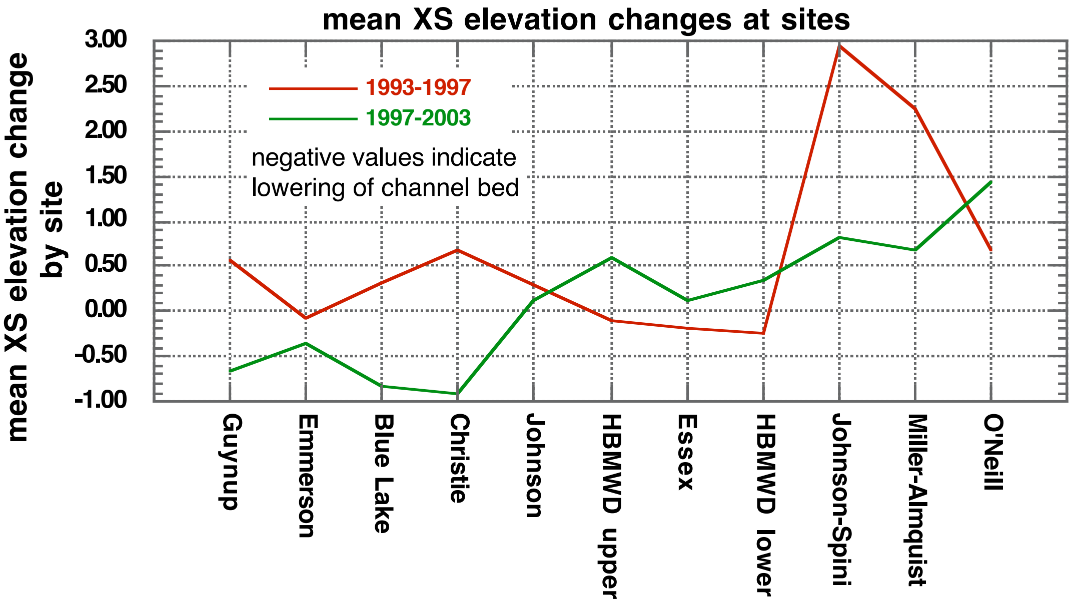

Fig. 10 Site mean changes in cross-section mean elevation for Mad River locations
Between 1993 and 1997 upstream sites mostly experienced a modest increase in mean elevation; in the downstream reach, the HBMWD and Essex sites underwent a small amount of lowering, while a large increase in mean elevation occurred at the sites downstream of Highway 299. After 1997, upstream sites mostly experienced mean lowering, while all downstream sites increased in mean elevation.

Table 6 and Fig. 10 demonstrate that from 1993-97 upstream sites mostly experienced a modest increase in mean elevation – i.e., channel filling, followed by consistent lowering of mean elevation from 1997-2003. In contrast, most downstream sites showed increasing mean elevation from 1993 on.

Thalweg elevation: Variations in thalweg elevation are typically greater than those of mean elevation; the more dramatic changes with time commonly reflect shifts in the positions of pools or riffles.

From 1993 to 1997, thalweg elevation at upstream sites commonly either increased or showed little change; but after 1997, these sites experienced moderate to substantial thalweg lowering. Figs. 11A and 12 clearly show this pattern of infilling followed by downcutting. The upstream thalweg elevations are now generally at or below the 1993 level.

In the downstream reach, between 1993 and 1997 the HBMWD and Essex sites underwent substantial mean thalweg lowering, while the sites downstream of Highway 299 experienced an increase in thalweg elevation (Figs. 11B and 12). After 1997, thalweg elevation increased at all downstream sites. At some cross-sections it outpaced the rise of mean elevation, leading to somewhat reduced confinement.

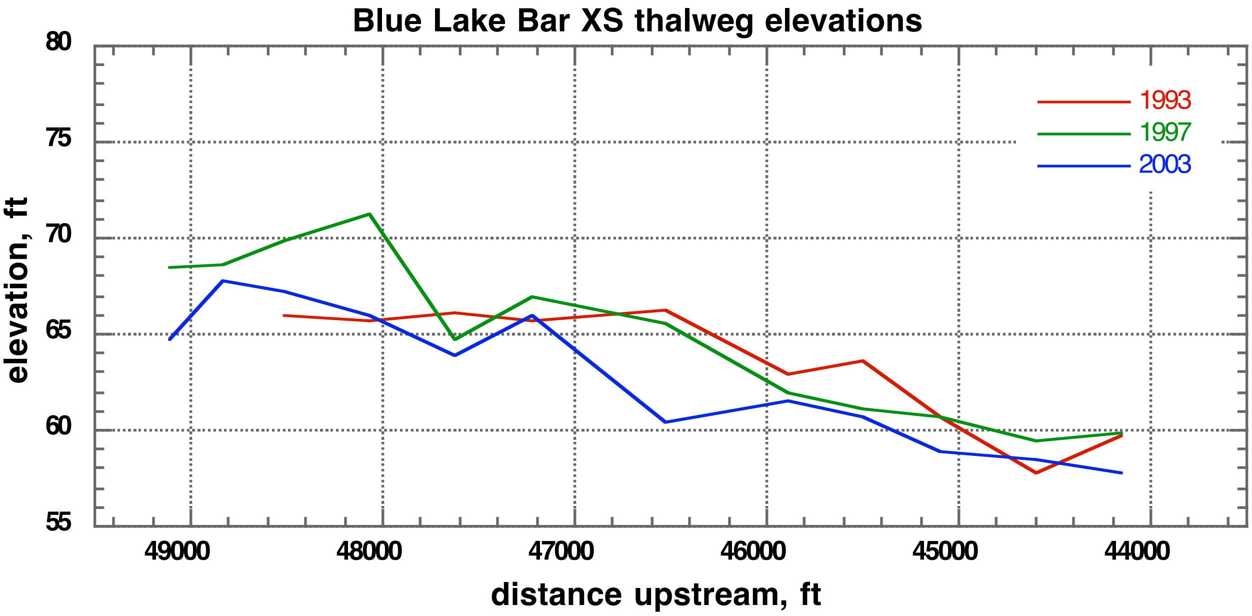

Fig. 11A Thalweg elevation long profiles of Mad River at Blue Lake Bar.

This plot is fairly typical of the pattern of thalweg elevation change seen at upstream sites. There was commonly either no change or an increase in thalweg elevation between 1993 and 1997, followed by a consistent decline in thalweg elevation in the period 1997-2003. The thalweg elevations are now generally at or below the 1993 level. Variations in thalweg elevation are typically greater than those of mean elevation; the more dramatic changes with time commonly reflect shifts in the positions of pools and riffles.

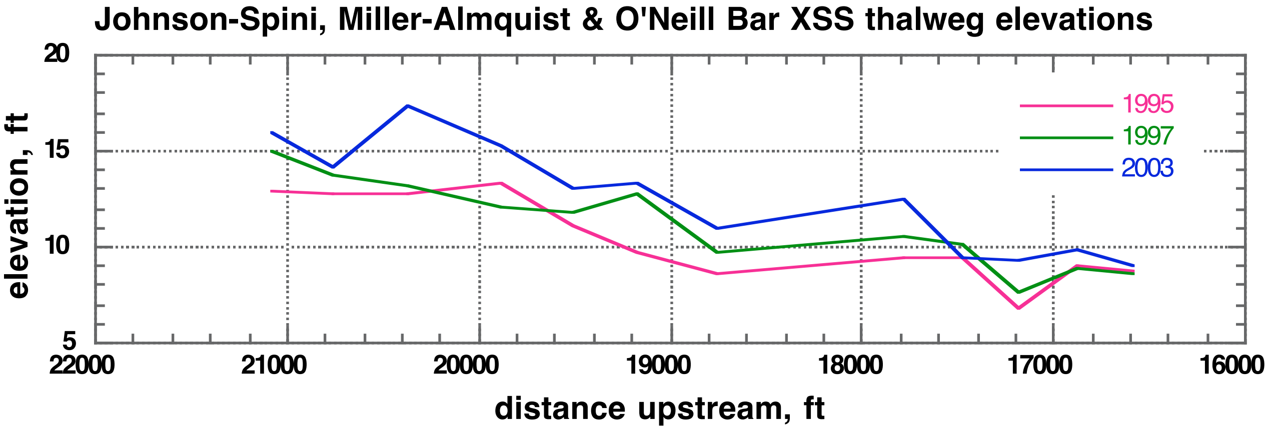

Fig. 11B Thalweg elevation long profiles of Mad River at Johnson-Spini, Miller-Almquist, and O'Neill Bars.

This plot illustrates the pattern of thalweg elevation change at sites downstream from the Hwy. 299 bridge. Since 1993 thalweg elevation has generally risen in downstream areas, in some cases outpacing the rise of mean elevation, leading to somewhat reduced confinement.

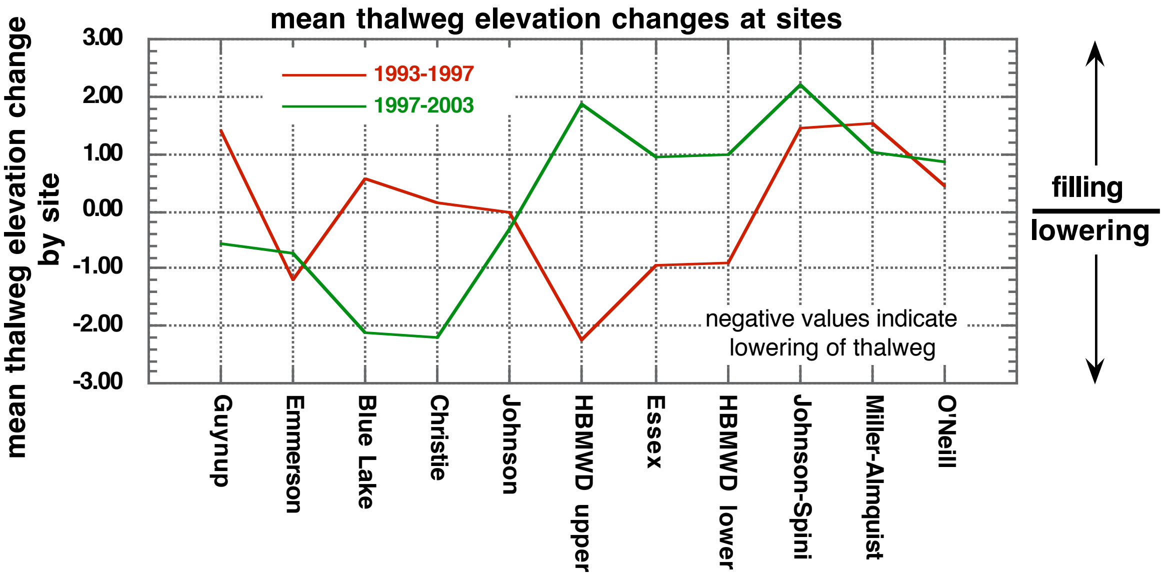

Fig. 12 Site mean changes in thalweg elevation for Mad River locations.
Between 1993 and 1997 upstream sites mostly experienced little overall change in mean thalweg elevation; in the downstream reach, the HBMWD and Essex sites underwent substantial mean thalweg lowering, while the sites downstream of Highway 299 experienced an increase in thalweg elevation. After 1997, upstream sites experienced moderate to substantial thalweg lowering, while all downstream sites increased in thalweg elevation.

Table 6 and Figs. 13A-B suggest that for the large upstream bars, the greatest changes in thalweg elevation tend to occur at the upstream and middle cross-sections. From 1993-97 thalweg elevation generally rose in upstream cross-sections and lowered in downstream cross-sections (Fig. 13A), while from 1997-2003 thalweg elevations lowered at nearly all cross-sections, regardless of position (Fig. 13B). The only overall pattern to emerge is that of persistent thalweg lowering at the downstream cross-sections.

At downstream sites (Fig. 13C), between 1993 and 1997 the thalweg lowered at upstream and middle cross-sections of the bars lying in the narrow gorge between the A&MRR and Highway 299 bridges. In contrast, the thalweg rose in the downstream cross-sections of these bars, and in all cross-sections downstream of the Hwy. 299 bridge. From 1997-2003, the thalweg rose in *all* downstream cross-sections. In contrast to the large bars upstream of the A&MRR bridge, these downstream sites show persistent thalweg rise at the downstream cross-sections.

Table 6 -- Spatial variation of changes in thalweg elevation

To reduce round-off errors in summing and averaging, quantities in this table are given to more significant figures than justified; individual values should be rounded to the nearest tenth before citation or use. Negative values indicate thalweg lowering.

	mean thalweg elevation change 1993-1997, ft			mean thalweg elevation change 1997-2003, ft		
Site	**upstream**	**middle**	**downstream**	**upstream**	**middle**	**downstream**
Guynup Bar	2.03	1.39	0.21	-0.30	-2.72	0.98
Emmerson Bar	-1.55*	-1.07*	-0.66*	-0.97*	0.08	-1.13
Blue Lake Bar	1.55*	-0.15	-0.15	-2.68	-2.13	-1.39
Christie Bar	0.74*	0.52*	-1.08*	-1.85*	-2.40*	-1.12*
Johnson Bar				1.31		-1.97
HBMWD upper	-2.57		-2.26	1.62		1.88
Essex Bar	-1.99		-0.96	1.38		0.95
HBMWD lower	-0.57*		-1.13	-0.06		1.67
Johnson-Spini Bar	2.71		-0.87	0.70		4.18
Miller-Almquist Bar	1.20		1.70	1.24		0.93
O'Neill Bar	0.90*		0.17	0.61		1.06

* indicates that the value includes one or more XSS that span fewer years than the column header indicates.

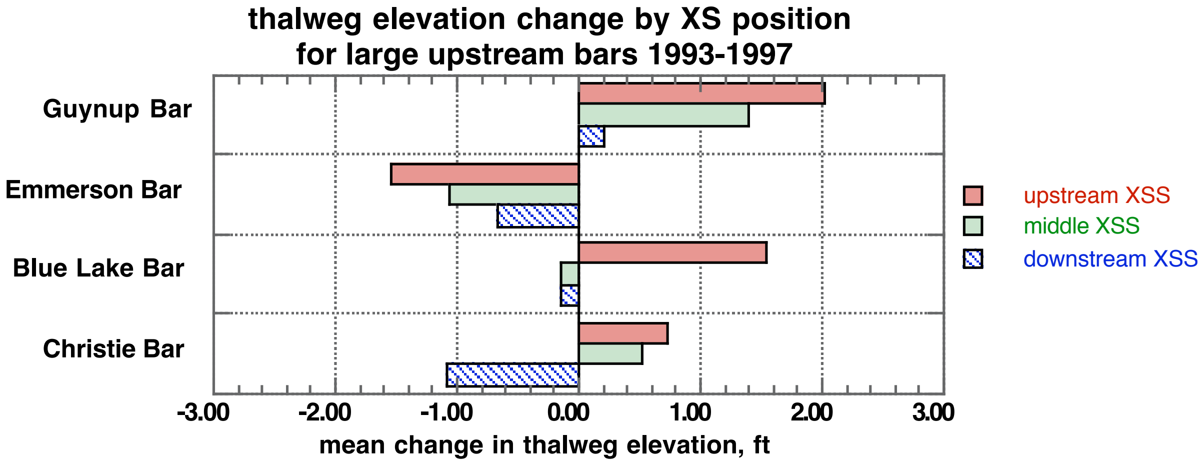

Fig. 13A Mean changes in XS thalweg elevation by position on bar at large upstream sites, 1993-97

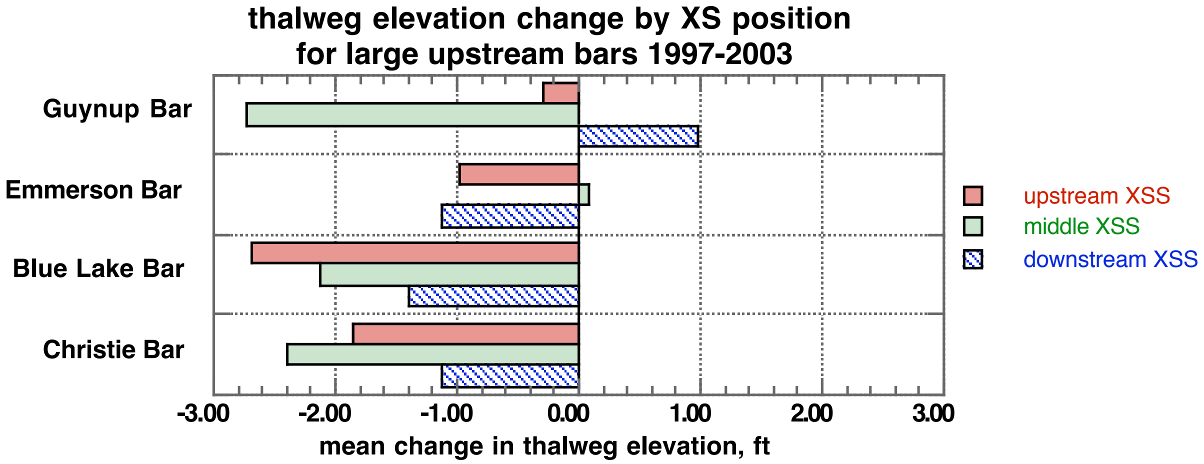

Fig. 13B Mean changes in XS thalweg elevation by position on bar at large upstream sites, 1997-2003

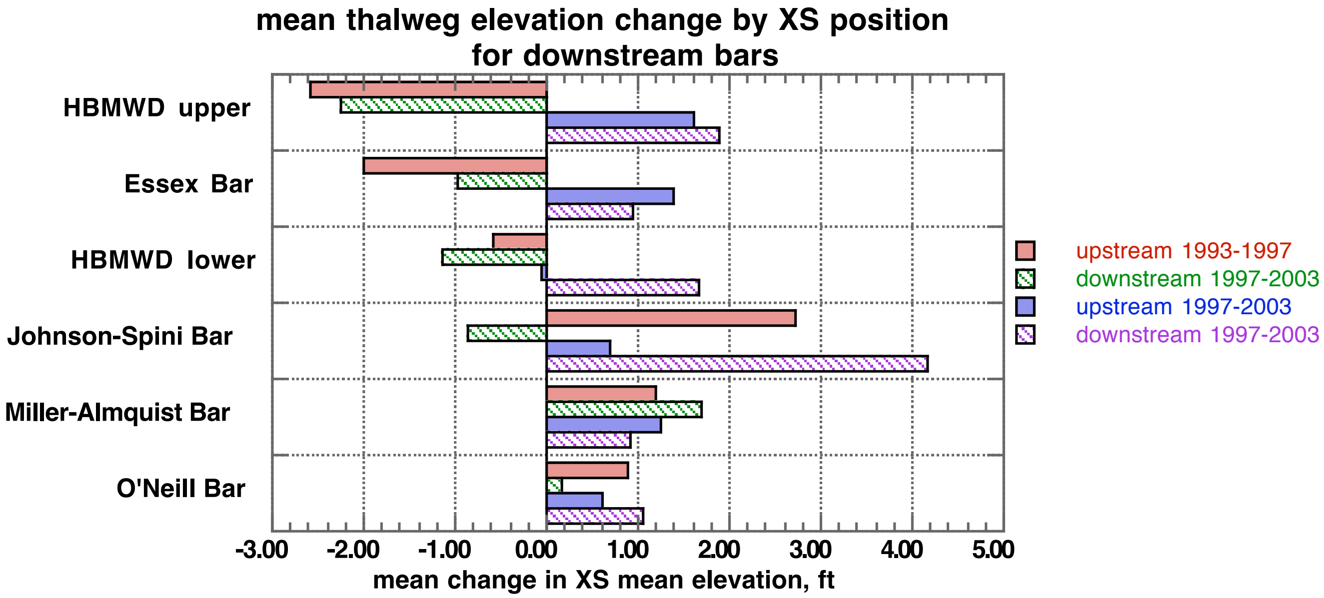

Fig. 13C Mean changes in thalweg elevation by position on bar at downstream sites, 1993-2003

Confinement: Confinement at the large upstream sites varies considerably in a downstream direction, but is generally lowest at the upstream and downstream ends of the bar, and reaches a maximum in the middle of the bar (Fig. 14). The pattern at downstream sites is broadly similar.

.At most upstream sites confinement since 1993 has either increased or stayed the same (Figs. 15, 16A-B and Table 7). At downstream sites confinement increased considerably between 1993 and 1997, and then mostly decreased between 1997 and 2003 (Figs. 15, 16C, Table 7). Today confinement at many of these downstream cross-sections is about the same or less than it was in 1993. This reflects a more rapid rise of the thalweg than of mean bar elevation as these sites have aggraded.

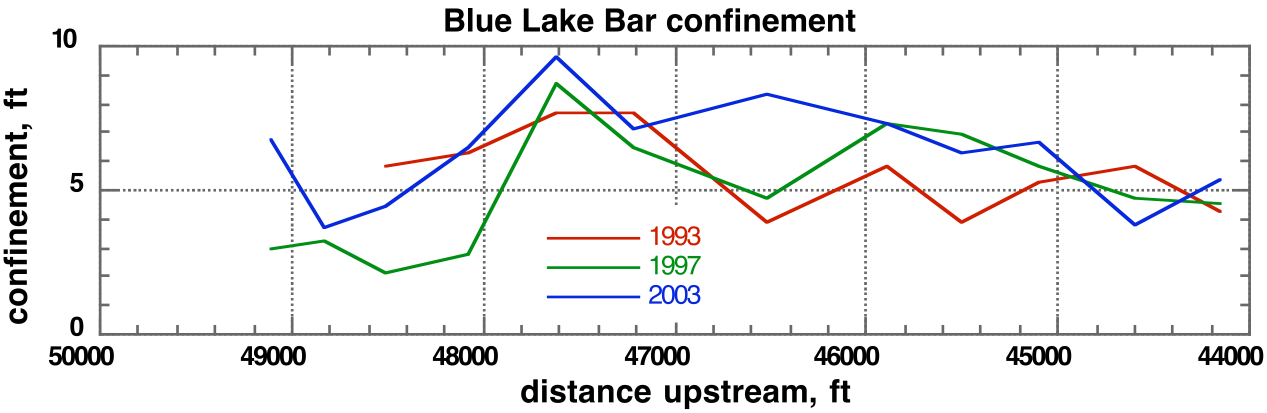

Fig 14 Variation of confinement with streamwise distance on Mad River at Blue Lake Bar. Confinement at upstream sites like this one varies considerably in a downstream direction, but is generally lowest at the upstream and downstream ends of the bar, and reaches a maximum in the middle of the bar. At most upstream sites confinement has either increased or stayed the same since 1993.

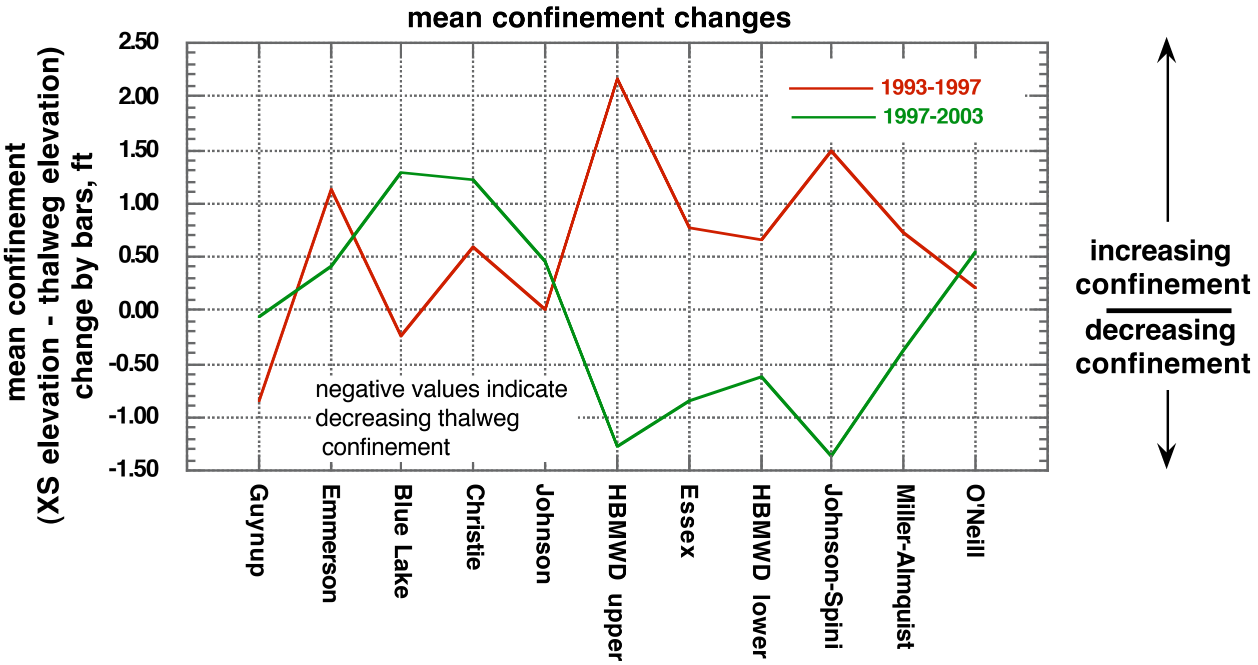

Fig. 15 Mean changes in confinement for Mad River sites.
From 1993-1997, upstream sites generally experienced a small increase in overall confinement while downstream sites had a moderate to substantial increase. From 1997-2003, upstream sites continued to increase in confinement, while downstream sites generally experienced a moderate reduction.

Table 7 -- Spatial variation of changes in confinement

To reduce round-off errors in summing and averaging, quantities in this table are given to more significant figures than justified; individual values should be rounded to the nearest tenth before citation or use. Negative values indicate reductions in channel confinement.

	mean confinement change 1993-1997, ft			mean confinement change 1997-2003, ft		
Site	**upstream**	**middle**	**downstream**	**upstream**	**middle**	**downstream**
Guynup Bar	-1.05	-1.73	0.46	-0.47	1.99	-1.33
Emmerson Bar	2.19*	0.23*	-0.10*	0.44*	0.00	0.73
Blue Lake Bar	-1.35*	0.38	0.68	2.23	1.43	0.00
Christie Bar	-0.11*	-0.24*	2.30*	-0.09*	2.23*	1.52*
Johnson Bar				-2.00		2.92
HBMWD upper	1.66		2.16	-1.29		-1.27
Essex Bar	1.67		0.77	-1.45		-0.84
HBMWD lower	0.54*		0.74	0.40		-1.32
Johnson-Spini Bar	0.28		4.73	0.54		-4.27
Miller-Almquist Bar	1.51		0.34	-0.80		-0.15
O'Neill Bar	-0.35*		0.58*	0.96		0.28

* indicates that the value includes one or more XSS that span fewer years than the column header indicates.

Table 7 and Figures 16A-C reveal no particularly compelling patterns of changes in confinement with position on the bar. Perhaps the most that can be said for the large upstream bars is that the downstream cross-sections most consistently show increases in confinement. No pattern is evident to us at the downstream sites.

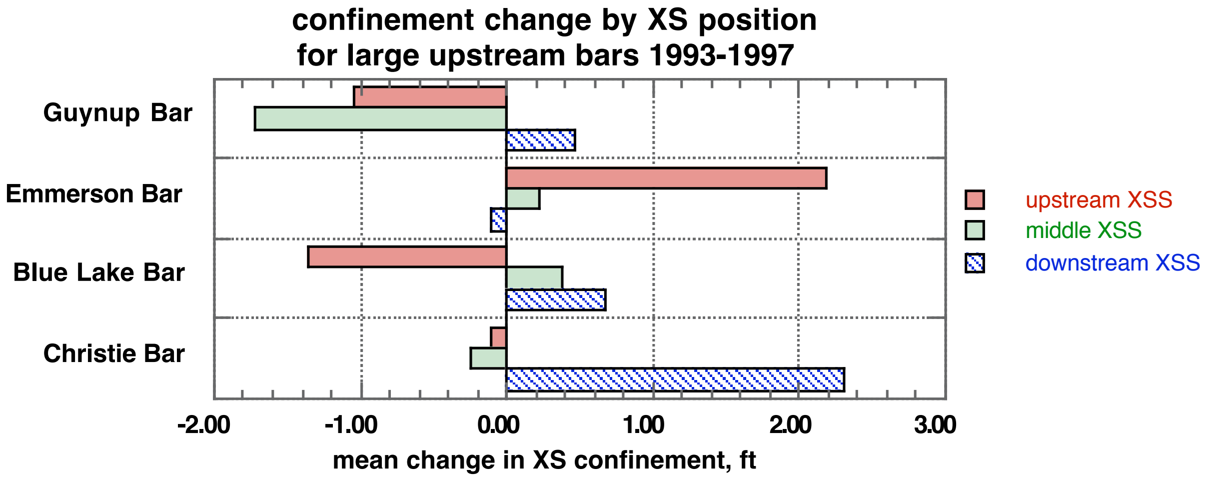

Fig. 16A Mean changes in confinement by position on bar at large upstream sites, 1993-97

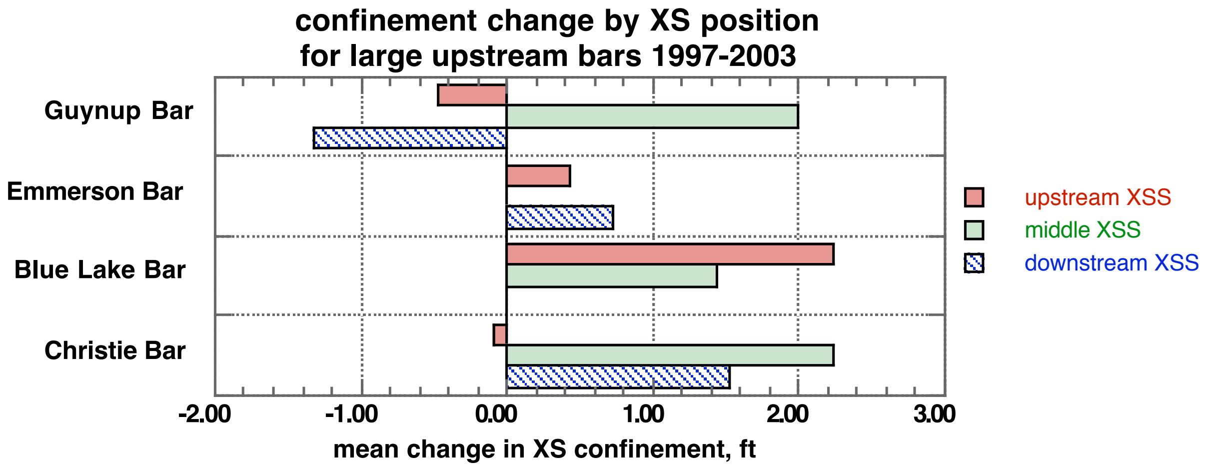

Fig. 16B Mean changes in confinement by position on bar at large upstream sites, 1997-2003

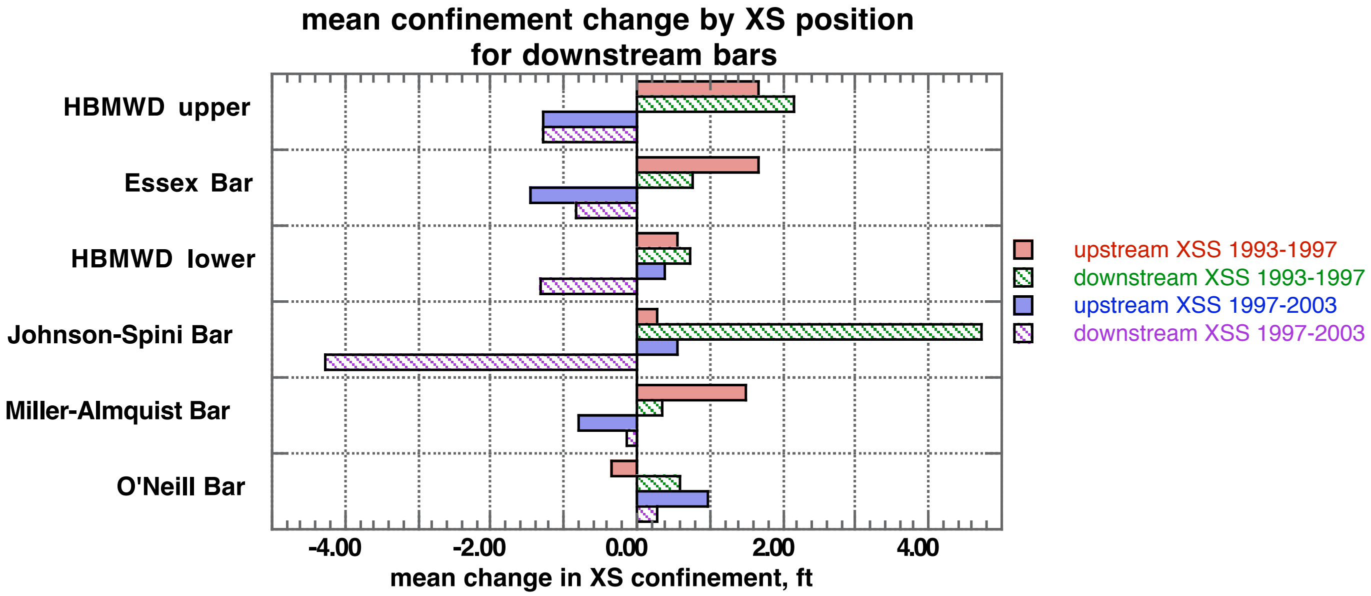

Fig. 16C. Mean changes in confinement by position on bar at downstream sites, 1993-2003

Temporal and Spatial Changes in Width

Width, as used here, is the distance from one side of the cross-section to the other measured at the reference elevation. These width measurements are subject to uncertainty due to the interpolation process used to estimate elevations at one-foot intervals across the channel. The steeper both banks are at the reference elevation, the more reliable the width estimates. Width differences of less than 5-10 feet are generally not meaningful as they may reflect only interpolation error rather than true changes.

Widths and width changes on the Mad River are strongly affected by geomorphic setting. At the largely unconfined upstream sites, cross-sections are wide and large increases in width – as much as 40–70% – are not uncommon (e.g., Figs. 17A and 18A). In contrast, the downstream sites, confined by resistant banks, are narrow and change in width by relatively small amounts, usually less than 10% (e.g., Figs. 17B and 18B).

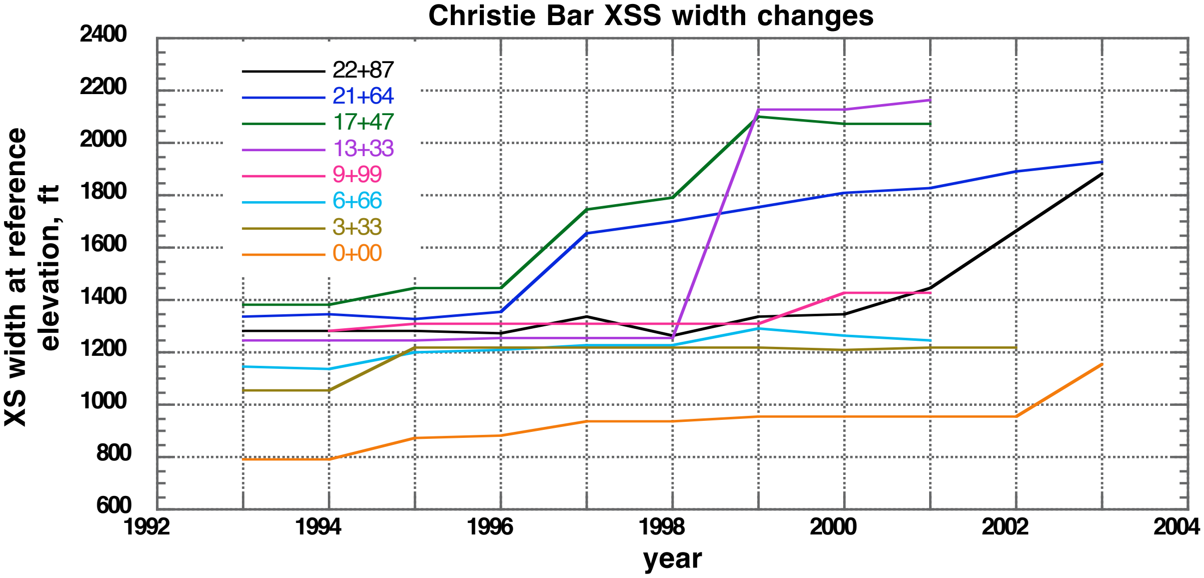

Fig. 17A Variation of cross-section width with time at Christie Bar middle and downstream XSS. Before 1996, cross-section width stayed either nearly constant or increased slightly at most XSS at this site. After 1996, width of the upstream XSS increased dramatically, while that of the downstream XSS stayed nearly constant.

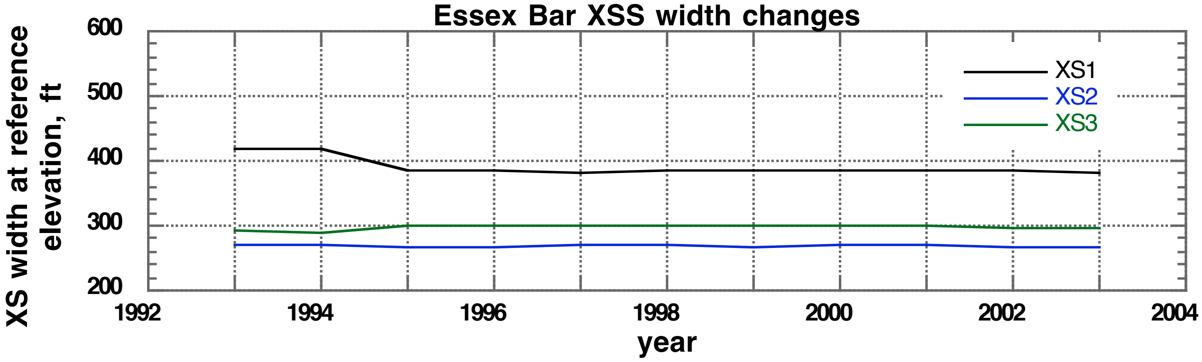

Fig. 17B Variation of cross-section width with time at Essex Bar XSS. Channel cross section width at this site has stayed essentially constant with time. This is typical of downstream cross-sections, where ability to widen is constrained by resistant banks.

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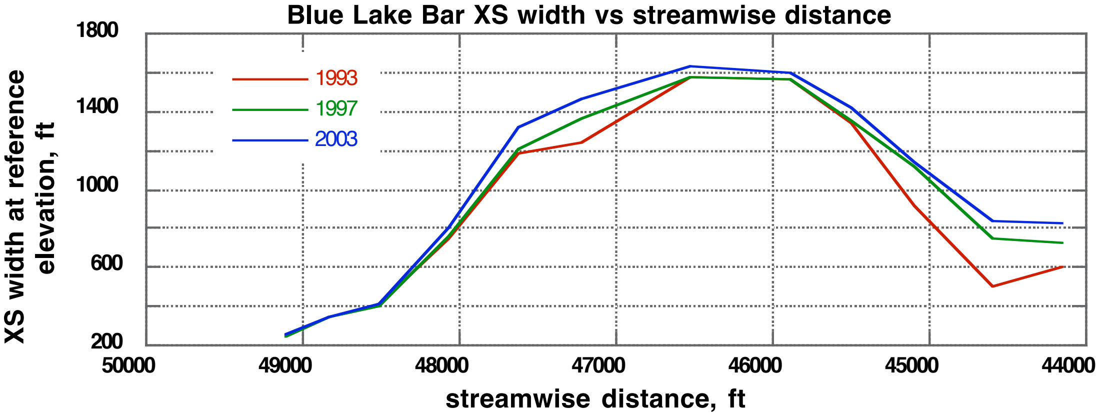

Fig. 18A Variation of cross-section width with streamwise distance on Mad River at Blue Lake Bar. Cross-section width at this site has increased consistently with time at all but the most upstream cross-sections, which are constrained by bank protection. This pattern of continuing widening is typical of upstream sites.

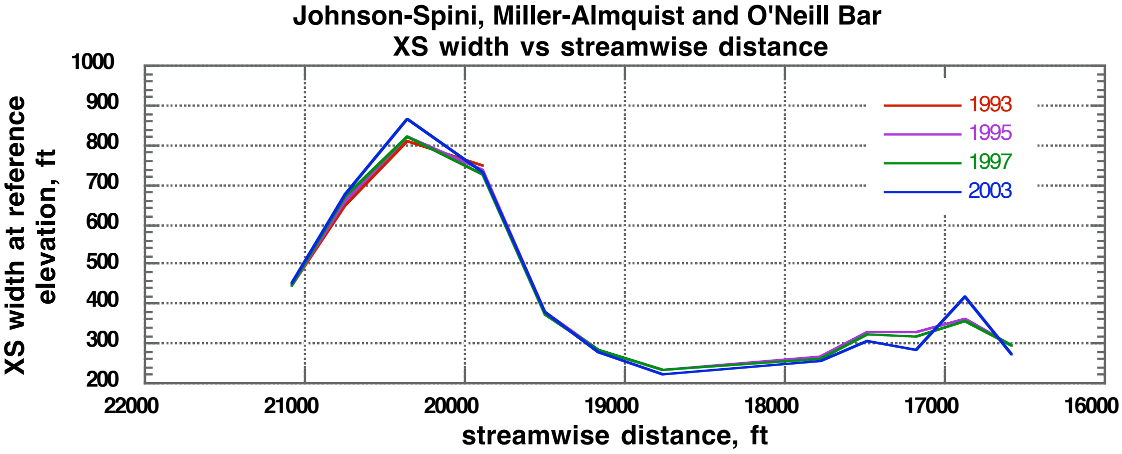

Fig. 18B Variation of cross-section width with streamwise distance on Mad River below Highway 299. Cross-section width at these sites has either stayed constant or diminished slightly with time. This is typical of downstream sites.

Since 1993, cross-sections at upstream sites have generally shown persistent widening (Figs. 17A, 18A, 19, 20A-B and Table 8), except where constrained by bank protection or resistant materials (e.g., downstream Emmerson Bar and upstream Blue Lake Bar.) No upstream cross-sections have diminished in width.

Cross sections at downstream sites have generally experienced either small amounts of narrowing or no change in channel width (Figs. 17B, 18B, 19, 20C and Table 8). The narrowing is sufficiently small that it lies within the margin of error of width measurements, and may actually reflect no change.

No clear pattern of variation of cross-section widening with position on the bar emerges from Table 8 or Figs. 20A-C. It does appear, however, that those areas that widened in 1993-97 generally continued to widen in 1997-2003, while those that narrowed in 1993-97 continued to narrow in 1997-2003.

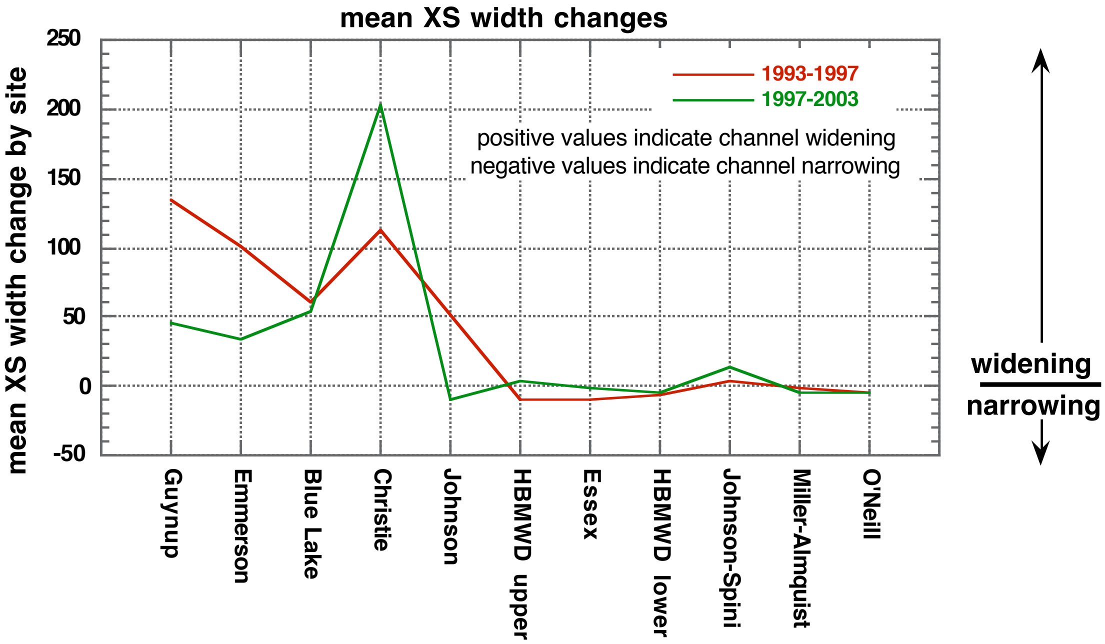

Fig. 19 **Site mean changes in cross-section width for Mad River locations.**
Upstream sites experienced large persistent cross-section widening from 1993 on, while downstream sites mostly experienced small amounts of narrowing or no change in width.

Table 8 -- Spatial variation of changes in XS width

To reduce round-off errors in summing and averaging, quantities in this table are given to more significant figures than justified; individual values should be rounded to the nearest ten before citation or use. Negative values indicate reductions in width.

	mean width change 1993-1997, ft			mean width change 1997-2003, ft		
Site	upstream	middle	downstream	upstream	middle	downstream
Guynup Bar	185	83	85	71	33	11
Emmerson Bar	205*	-1*	-5*	64*	-1	9
Blue Lake Bar	5*	40	142	36	60	73
Christie Bar	55*	227*	115	148*	506*	89*
Johnson Bar				-5		-15
HBMWD upper	-12		-9	4		3
Essex Bar	4		-10	-2		-2
HBMWD lower	-9*		-4	-1		-7
Johnson-Spini Bar	12		9	4		47
Miller-Almquist Bar	-6		-1	4		-8
O'Neill Bar	-3*		-5*	-13		1

* indicates that the value includes one or more XSS that span fewer years than the column header indicates.

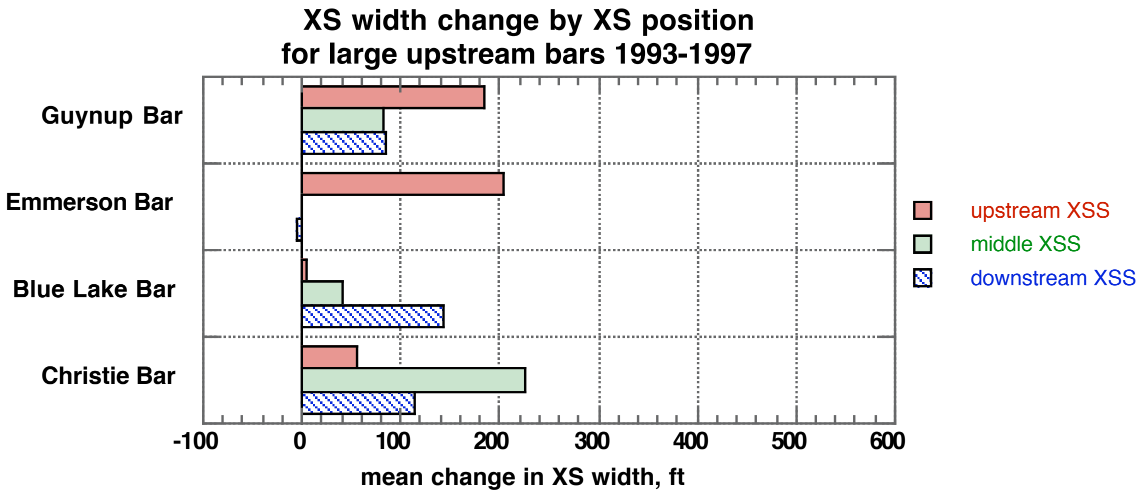

Fig. 20A Mean changes in cross-section width by position on bar at large upstream sites, 1993-97

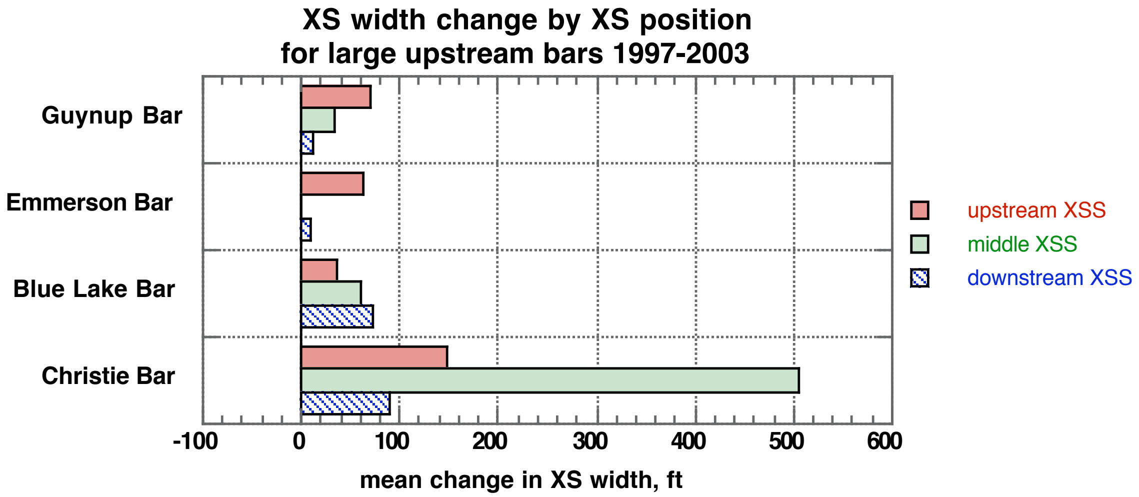

Fig. 20B Mean changes in cross-section width by position on bar at large upstream sites, 1997-2003

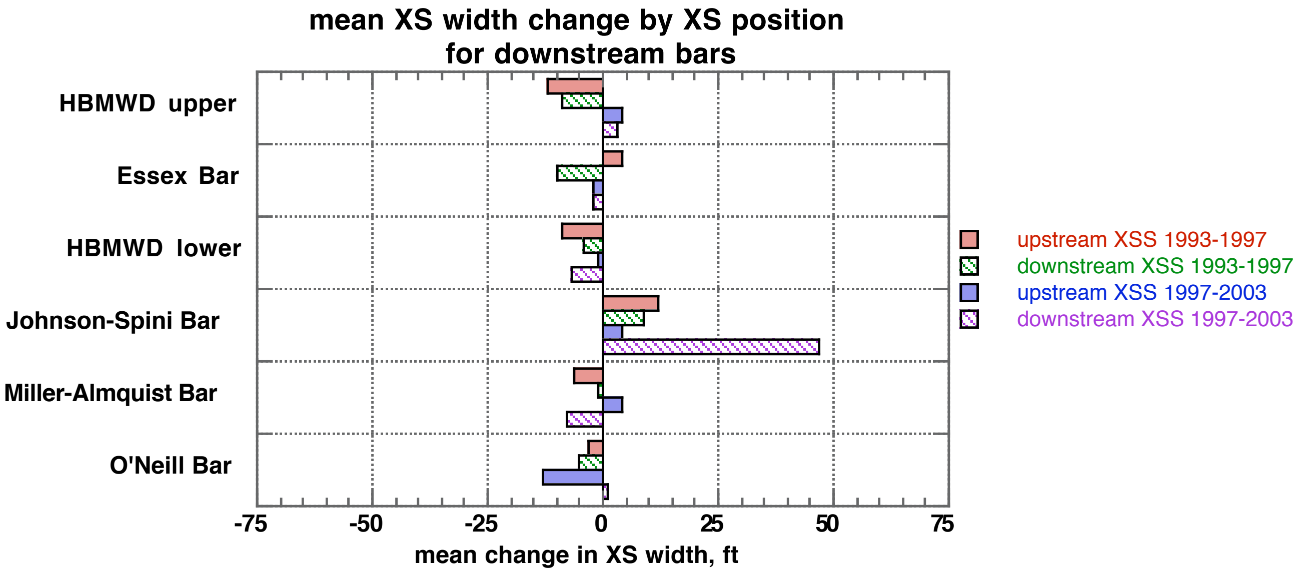

Fig. 20C Mean changes in cross-section width by position on bar at downstream sites, 1993-2003

Temporal and Spatial Changes in Cross-Section Area

Cross-section area refers to the area lying between the reference elevation and the ground surface in the cross-section (Fig. 2). Cross-section area is the most important measure of the size of the channel, incorporating as it does both cross-section width and mean elevation. Change in cross-sectional area is the most fundamental measure of channel enlargement or filling.

Fig. 21 shows the variation of 2003 cross-section area with distance downstream. Cross-section areas in the unconfined upstream reach are presently mostly larger than 4000 ft^2;; those in the downstream reach are mostly smaller than 4000 ft^2, reflecting its confined nature.

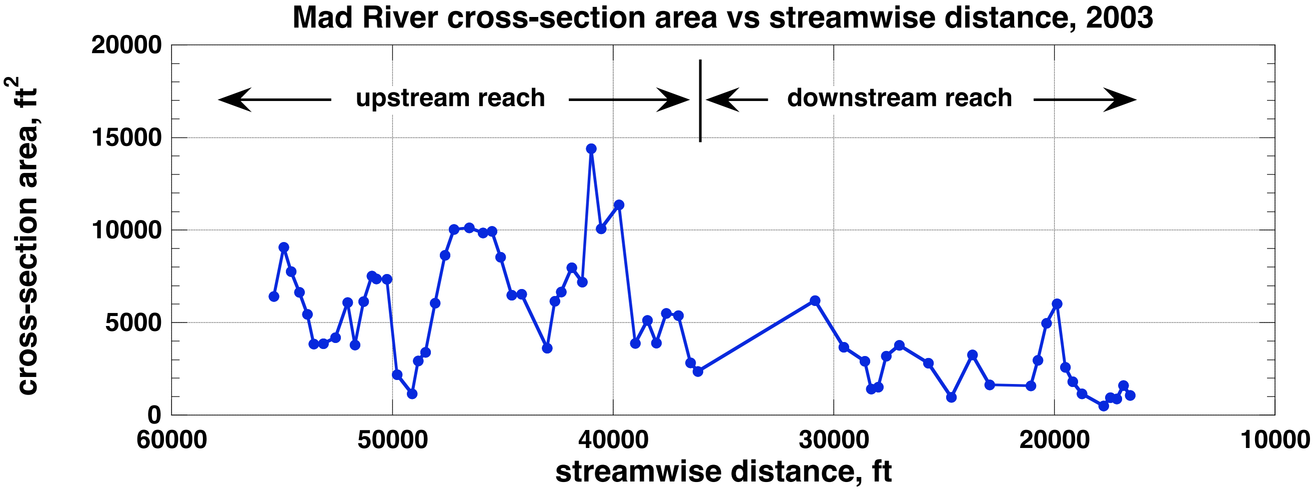

Fig. 21 Variation of cross-section area along the Mad River.
Upstream cross-section areas are presently mostly > 4000 sq. ft; those downstream are mainly < 4000 sq. ft.

Figure 22A is a typical example of how cross-section area changed with time at upstream sites. Between 1993 and 1997, cross-sections at upstream sites generally underwent modest changes in area of less than a few hundred sq. ft. (see Figs.22A, 23A, 24, 25A, and Table 9.) Some cross-sections enlarged while others filled (Fig. 25A), so the aggregate effect was one of little overall change. From 1997 to 2003, however, nearly all upstream cross-sections enlarged significantly, commonly by 1000 sq. ft or more (see Figs.22A, 23A, 24, 25B, and Table 9.) Since 1997, upstream cross-sections have steadily enlarged, typically at rates of 100 to 400 ft^2/yr. Channel widening (i.e., bank erosion), not channel downcutting is the main agent of enlargement (see Figs. 20A and 20B.)

Since 1993, most downstream-site cross-sections have experienced reductions in area; Figures 22B and 23B exemplify the pattern. In the period 1993 -1997, cross-sections between the A&MRR and Hwy. 299 bridges changed relatively little in area, but those downstream from Hwy. 299 all showed substantial filling (Figs. 22B, 23B, 24, 25C, and Table 9). Since 1997 nearly all the downstream cross-sections have undergone continued modest filling (Fig. 25C, Table 9). The reduction in area – i.e. filling - at downstream sites has been accomplished mainly by increase of bed and bar elevations (see Figs. 9C and 13C), rather than by channel narrowing.

Table 9 and Figures 25A-C suggest no preferred pattern of area changes related to cross-section position on a bar.

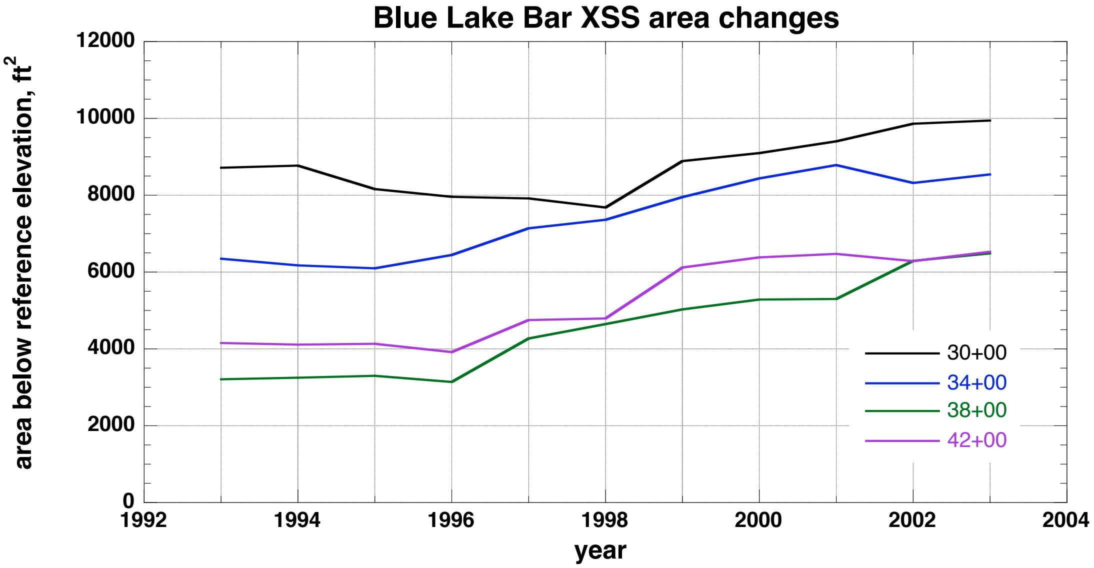

Fig. 22A Variation of cross-section area with time at Blue Lake Bar downstream cross-sections. Between 1993 and 1996 channel cross-section area at these XSS stayed essentially constant; since 1997 these cross-section areas have steadily increased at rates of 250 - 400 ft^2/yr, reflecting channel widening. This pattern is typical of upstream XSS.

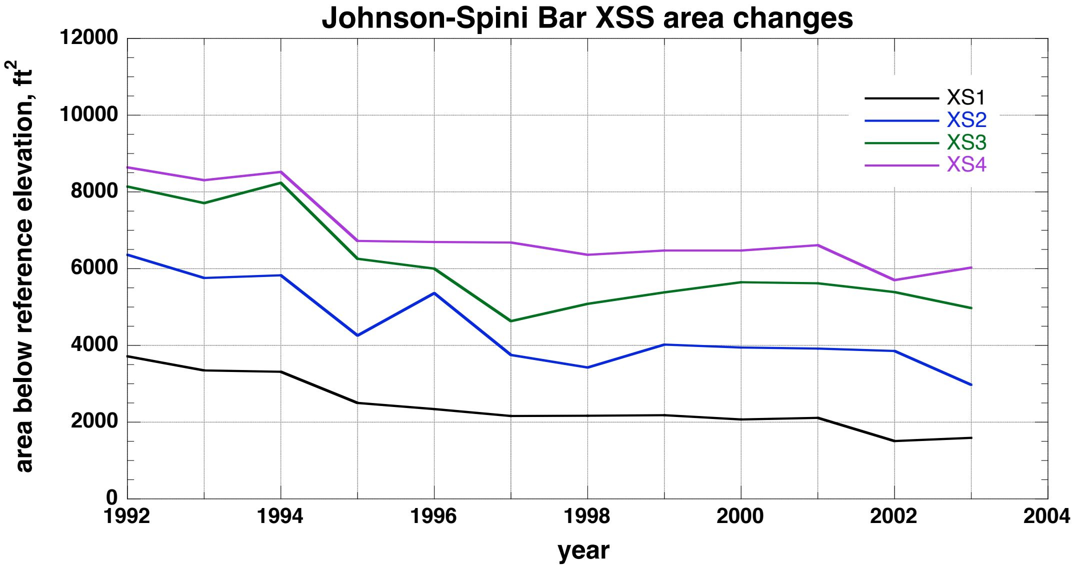

Fig. 22B Variation of cross-section area with time at Johnson-Spini Bar cross-sections. Between 1993 and 1997 channel cross-section area at these XSS diminished considerably, reflecting aggradation; since 1997 cross-section areas have stayed essentially constant or have diminished slightly. This pattern is typical of downstream sites.

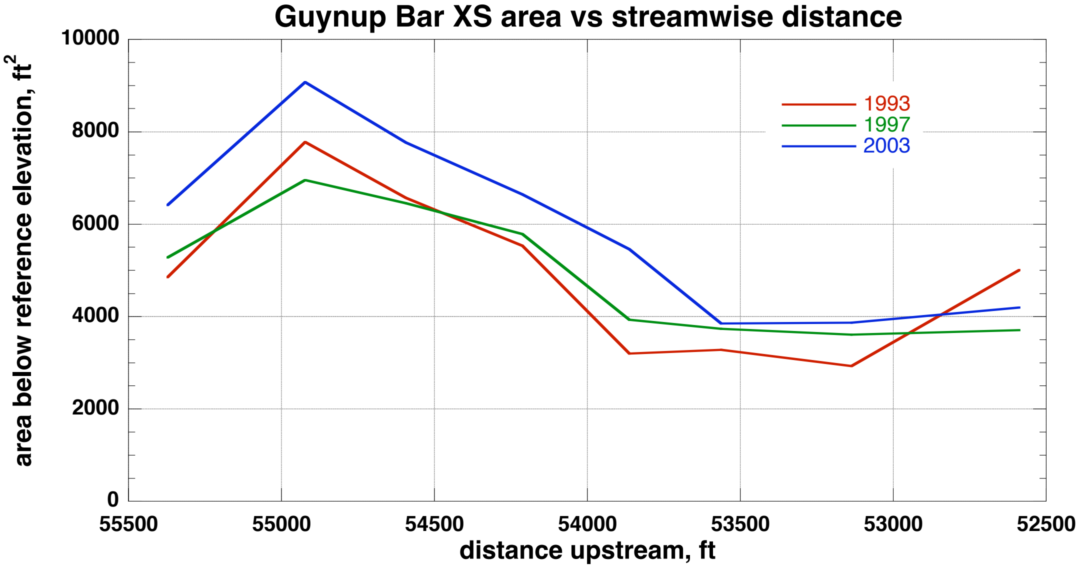

Fig. 23A Variation of cross-section area with streamwise distance on Mad River at Guynup Bar.
This plot is typical of the pattern of cross-sectional area change at upstream sites. Since 1993 cross-sectional area has consistently increased in downstream areas. The most dramatic increases occurred after 1997.

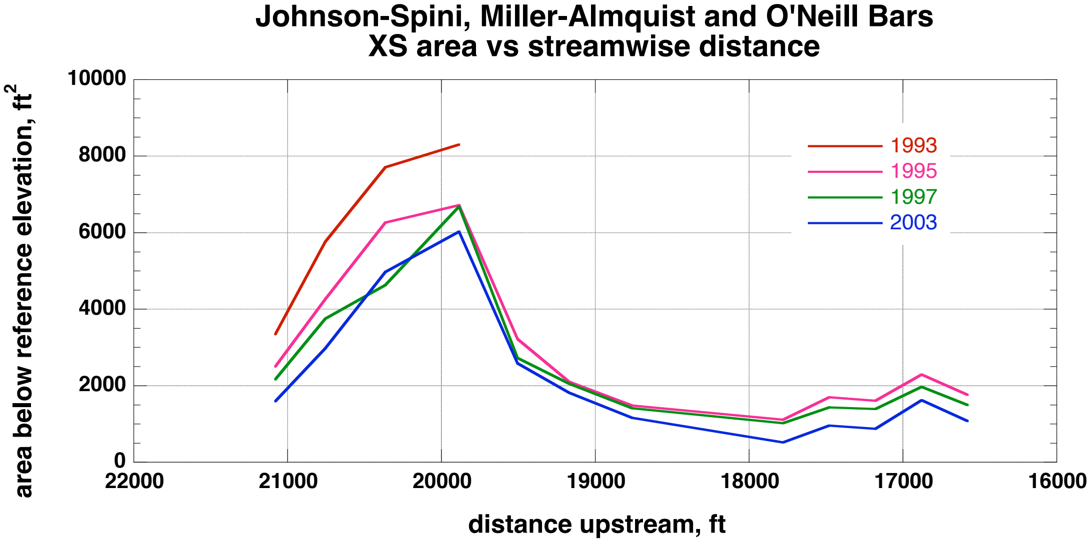

Fig. 23B Variation of cross-section area with streamwise distance on Mad River below Highway 299.
This plot is typical of the pattern of cross-sectional area change at downstream sites. Since 1993 cross-sectional area has consistently decreased in downstream areas.

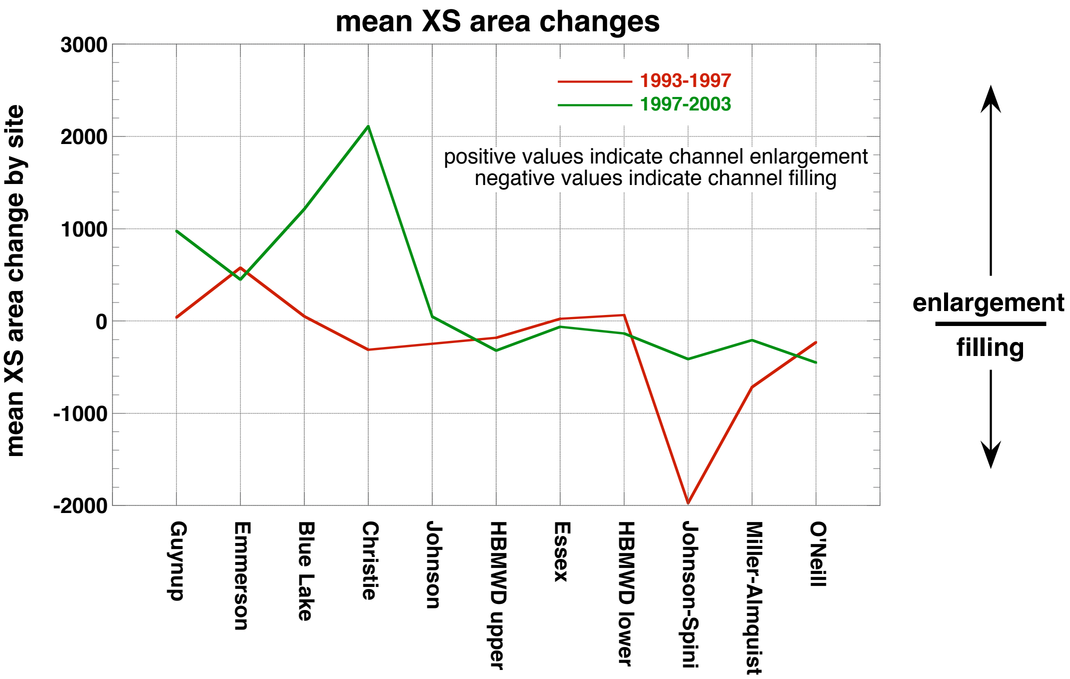

Fig. 24 **Site mean changes in cross-section area for Mad River locations.** Between 1993 and 1997 mean cross-section area changed relatively little at upstream sites and in the HBMWD-Essex downstream reach. The sites downstream of Highway 299 all showed considerable filling. Since 1997, the upstream sites have experiences significant channel enlargement, while the downstream sites have all undergone modest filling.

Table 9 -- Spatial variation of changes in XS area

To reduce round-off errors in summing and averaging, quantities in this table are given to more significant figures than justified; individual values should be rounded to the nearest ten or hundred before citation or use. Negative values indicate reductions in area

	mean XS area change 1993-1997, ft^2			mean XS area change 1997-2003, ft^2		
Site	**upstream**	**middle**	**downstream**	**upstream**	**middle**	**downstream**
Guynup Bar	-65	594	-311	1355	819	374
Emmerson Bar	553*	1286*	861*	812*	-44	133
Blue Lake Bar	-163*	-83	414	542	1483	1856
Christie Bar	-631*	867	-798*	3266	3096*	-76*
Johnson Bar				640		-546
HBMWD upper	262		-182	-93		-323
Essex Bar	128		24	6		-61
HBMWD lower	-43*		156	-135		-138
Johnson-Spini Bar	-1598		-3079	-669		341
Miller-Almquist Bar	-1001		-491	-136		-246
O'Neill Bar	-485*		-673*	-488		-427

* indicates that the value includes one or more XSS that span fewer years than the column header indicates, or which includes estimated XS areas for missing years.

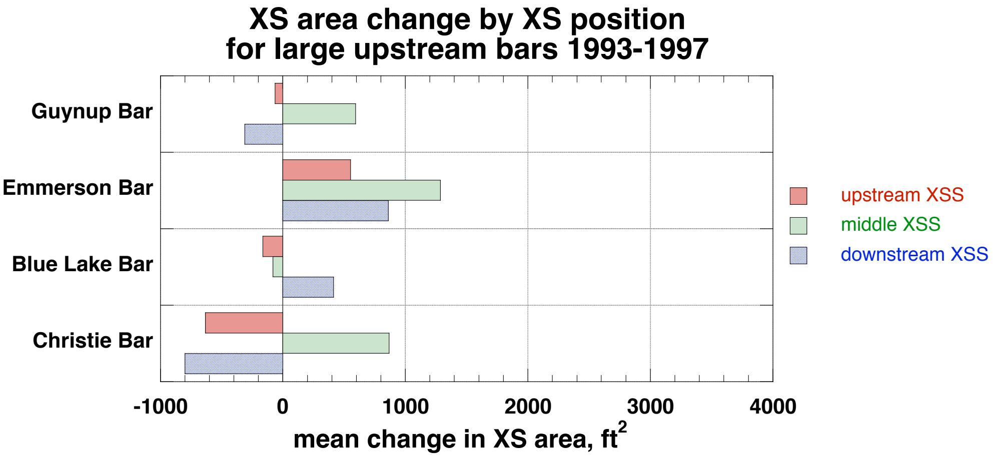

Fig. 25A Mean changes in cross-section area by position on bar at large upstream sites, 1993-97.

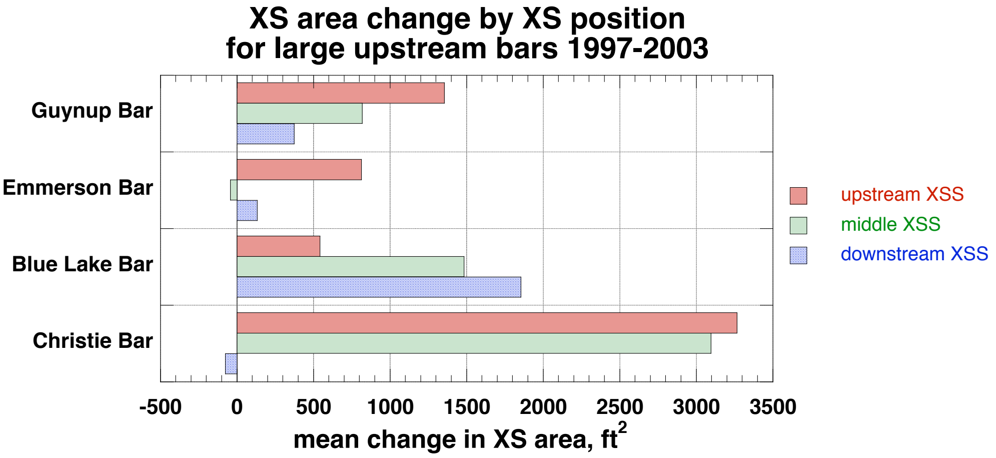

Fig. 25B Mean changes in cross-section area by position on bar at large upstream sites, 1997-2003.

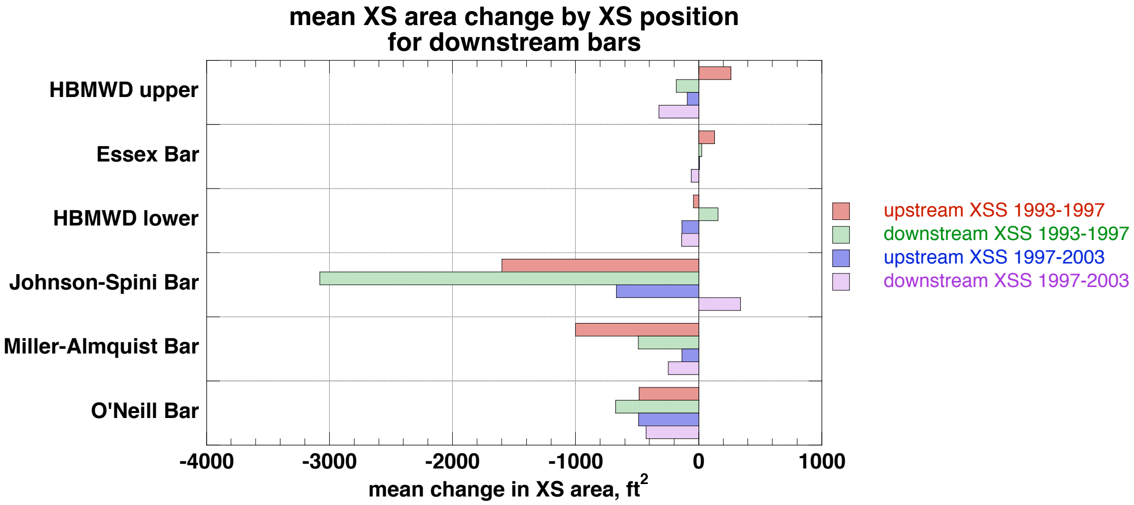

Fig. 25C Mean changes in cross-section area by position on bar at downstream sites, 1993-2003.

Temporal and Spatial Changes in Channel Volume

Computation of channel volume: Channel volume, as used in this report, is the volume between an imaginary surface defined by the reference elevations, and the actual ground surface beneath. Channel volume was computed between pairs of adjacent cross-sections using the *double-end-area* (DEA) method: the areas of the two cross-sections are averaged and then multiplied by the centerline (CL) distance between them (Fig. 22). These volumes can then be summed to yield total channel volume. Subtracting the channel volumes of different years gives the change in channel volume between those years. Note that the closer the cross-sections are to each other, the smaller the error in the volume estimate.

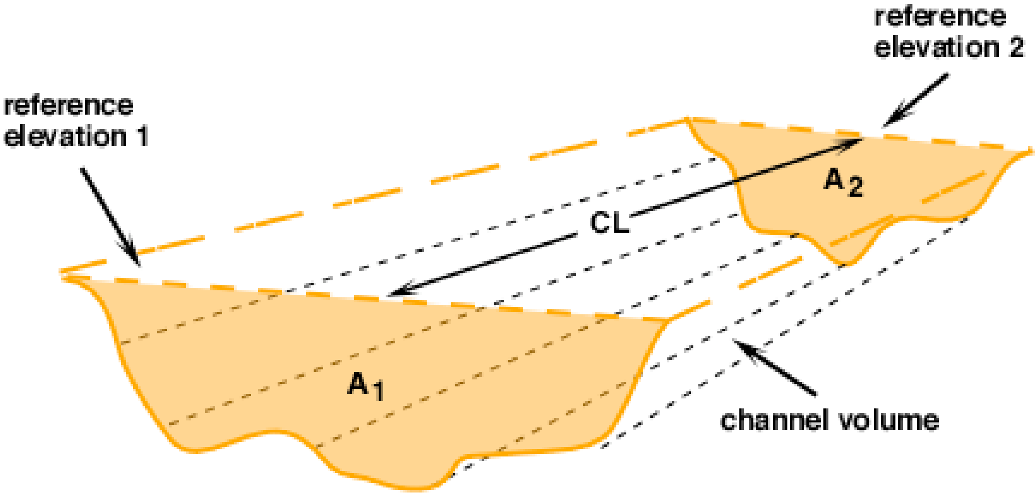

Fig. 26 Definition sketch for DEA computation of channel volume between two cross-sections.
Channel volume between XSS = $(A_1 + A_2)/2$ x CL length

A more direct way to compute *changes* in channel volume, and the method used in this study, is to compute the change in area at each cross-section for the period of interest, then to average the changes at the two ends and multiply by CL length. That is:

$$\Delta\text{Volume} = (\Delta A_1 + \Delta A_2)/2 \times \text{CL length}$$

where: $\Delta A_1 = (A_{1,\,end} - A_{1,\,start})$ change in area at XS1 between starting and ending dates
$\Delta A_2 = (A_{2,\,end} - A_{2,\,start})$ change in area at XS2 between starting and ending dates

Computing the volume change between any two years thus requires four cross-section areas.

Because of our convention of always subtracting starting areas from ending areas, positive changes in volume indicate enlargement of the channel, while negative values indicate filling, i.e., reduction in volume.

Missing cross-sections: Missing cross-sections are a principal difficulty and source of error in computing volume changes in this study. Most of the missing cross-sections are in the upstream reach, and are due either to 1) installation of the cross-section after 1993 or 1997; or 2) abandonment or realignment of a cross-section due to shifting of the river channel. A small number resulted from survey errors or oversights.

Two strategies can be used to deal with missing cross-sections: 1) to omit the cross-section from volume computation, which has the disadvantage of substantially increasing the distance between cross-sections and thus significantly increasing error; or 2) to estimate the missing cross-section areas. We chose the latter.

We estimated missing areas using the following procedure:

1) at near-by cross-sections compute the average ratio of missing-year XS area to XS area of preceding or subsequent years, giving greatest weight to ratios from the nearest cross-sections;

2) at the missing site, multiply the XS area of the preceding or subsequent year, as appropriate, by the ratio from step 1. This yields a reasonable estimate of the missing area.

Our complete estimates of channel area and volume are available electronically in the *Mad R XSS Data Summary 2003* spreadsheet.

DEA calculations of volume may contain substantial error wherever channels contain large unmeasured variations in area (i.e., width and elevation) between cross-sections. The DEA method assumes smooth, regular variation in area between cross-sections. It is most accurate where channels are uniform and cross-sections closely spaced. Volumes determined between widely spaced cross-sections which differ greatly in shape and area are likely to contain significant error (e.g., the reach between Johnson Bar XS J-4 and HBMWD XS8 or that between Blue Lake Bar XS 42+00 and Christie Bar XS CH-1). For the most part, however, the DEA method yields reasonable volume estimates on the Mad; mean spacing of cross-sections is about 550 ft in the upstream reach and 700 ft in the more uniform downstream reach.

Figures 27, 28, and Table 10 summarize the spatial and temporal changes in Mad River channel volumes. For the upstream reach, between 1993 and 1997 the three upstream bars experienced moderate net channel enlargement, while the two downstream bars underwent slightly greater net filling, leaving the reach overall slightly aggraded. It is evident from Fig 28 that the aggradation took place chiefly in 1993-94. From 1997 to 2003, the upstream sites, with the exception of Johnson Bar, experienced massive channel enlargement due mainly to channel widening and bank erosion. Our estimate of 960,000 cu.yd. net loss in 1997-2003 compares well with Fehlman's (2004, p. 7) statement that net loss was "more than 800,000 cubic yards." Figure 24 makes it clear that most of the enlargement occurred in 1998–2000, and that the rate of enlargement has been diminishing since 2001. Overall, from 1993-2003, the upstream reach lost about 945,000 cu. yd., or 95,000 cu. yd./year.

With the exception of Essex Bar in 1993-1997, all downstream sites have experienced persistent net aggradation (filling) since 1993. From 1993-2003, the downstream reach gained about 425,000 cu. yd., or 43,000 cu. yd./year.

In summary, the large unconfined upstream sites have been major losers of stored sediment, largely through bank erosion rather than downcutting, while the confined or semi-confined downstream sites have undergone significant aggradation. The two do not balance however: upstream erosion is about twice the rate of downstream deposition, and from 1993-2003 the Mad experienced a net loss of about 520,000 cu yd. of bed and bank material, or 52,000 cu. yd./year.

Table 10 -- Spatial variation of changes in volume

To reduce round-off errors in summing and averaging, quantities in this table are given to more significant figures than justified; individual values should be rounded to the nearest thousand before citation or use. Negative values indicate filling

	total volume change in period for site, cu. yd.		
Site	**1993-1997**	**1997-2003**	**1993-2003**
Guynup Bar	3927	110085	114011
Emmerson Bar	100082	52741	152823
Blue Lake Bar	14627	362376	377003
Christie Bar	-72357	512872	440515
Johnson Bar	-60876	-78016	-138892
HBMWD upper	-44254	-72074	-116328
Essex Bar	2032	-2054	-22
HBMWD lower	-27966	-46560	-74526
Johnson-Spini Bar	-116224	-19466	-135690
Miller-Almquist Bar	-30682	-19892	-50574
O'Neill Bar	-27761	-20006	-47767
Total upstream	-14597	960058	945461
Total downstream	-244854	-180052	-424907
Total Mad	-198575	780005	520554

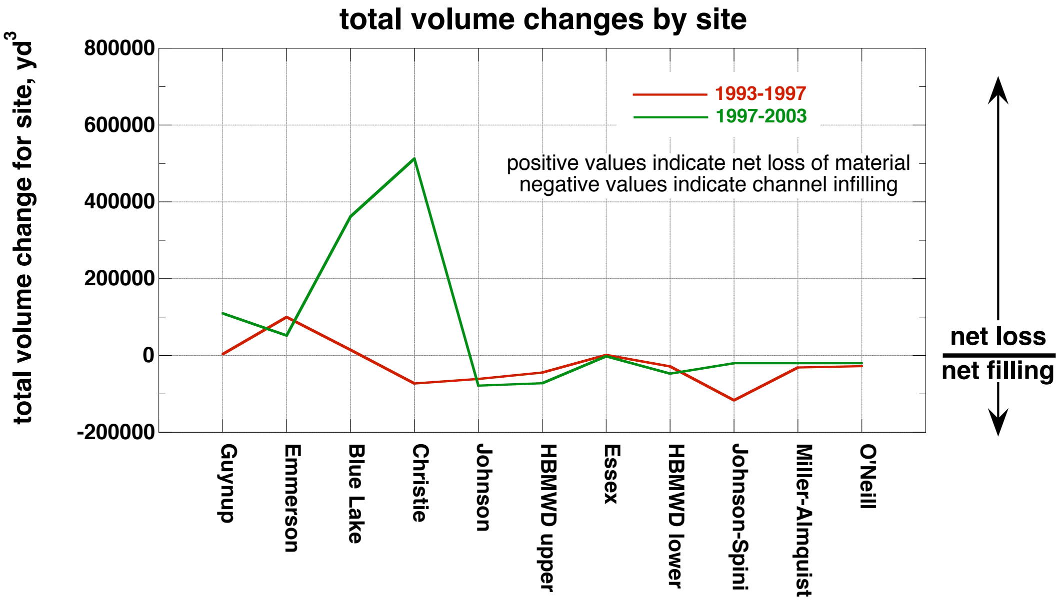

Fig. 27 Changes in channel volume for Mad River sites

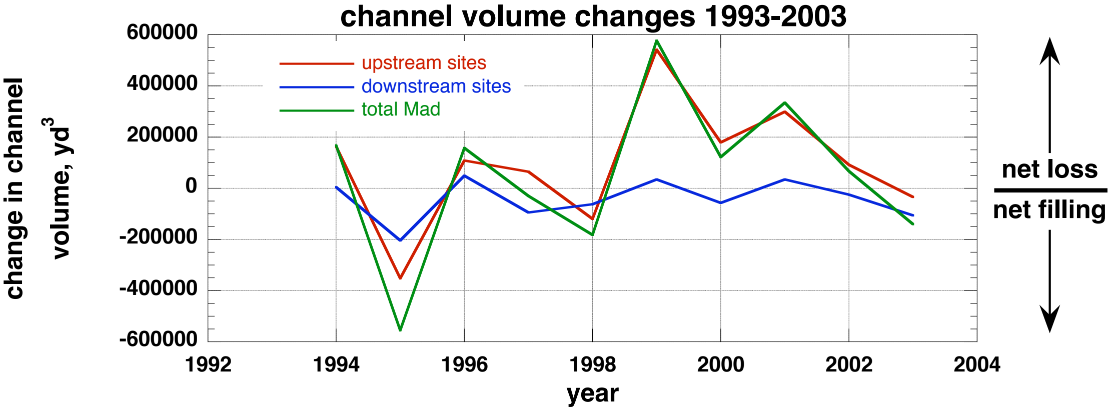

Fig. 28 Changes in channel volume with time for Mad River.
The year indicated on the axis is that of the end of the computation period, e.g., the value plotted at "1994" is the volume change for the 1993-94 period. Negative values indicate channel aggradation (filling).

Temporal and spatial changes in longitudinal slope

We estimated longitudinal channel slope by plotting thalweg elevation vs. streamwise distance for each cross-section, fitting the data with a straight line, and calculating its slope. Separate fits were made for upstream and downstream reaches. As a check, we used the same procedure with the XS mean elevations. Table 11 summarizes our results. The slope estimates made using XS mean elevation are consistently larger than those based on thalweg elevations. We believe that the thalweg elevations are to be preferred, for they do not depend on the choice of a reference elevation as XS mean elevations do. From 1993-2003 upstream slope increased slightly while downstream slope decreased by almost the same amount.

Table 11 -- Estimates of longitudinal channel slope

	longitudinal slope			
year	**upstream thalweg**	**upstream mean elevation**	**downstream thalweg**	**downstream mean elevation**
1993	0.00224	0.00237	0.00193	0.00193
1997	0.00248	0.00249	0.00154	0.00172
2003	0.00250	0.00245	0.00155	0.00164
2003-1993	0.00028	0.00008	-0.00038	-0.00029

Summary of cross-section geomorphic changes

Table 12 summarizes the findings of the geomorphic analysis. Profound differences exist in the responses of the mostly unconfined upstream reach and the confined or semi-confined downstream reach. Between 1993 and 1997, the upstream reach underwent an episode of overall mild aggradation, with modest increases in mean and thalweg elevation being balanced by increases in cross-section width and area due to bank erosion. From 1997 to 2003, however, the upstream reach experienced moderate decreases in mean and thalweg elevation together with large increases in cross-section width and area from bank erosion, thus leading to persistent channel enlargement and loss of material from storage. Although the channel continues to enlarge, the rate of enlargement appears to have declined since 2001. Confinement has increased slightly due to thalweg lowering. Longitudinal slope increased by about 0.0003 since 1993. Nearly all of this increase occurred from 1993-97.

In contrast, the downstream reach has undergone mainly aggradation since 1993. Mean and thalweg elevations have steadily increased, and, with width staying essentially constant, cross-section area has decreased as the bed has raised. Net channel volume decreased substantially, reflecting bar growth. Confinement decreased modestly where thalweg elevations rose more rapidly than mean bar elevation. Longitudinal slope decreased by about 0.0004 since 1993; again, nearly all of this occurred in 1993-97.

It should be noted that our conclusions regarding volume loss in the upstream reach and aggradation in the downstream reach are consistent with those of Kondolf and Lutrick (2001) and Knuuti (2003).

Table 12 -- Summary of Mad River cross-section changes, 1993-2003

	upstream sites		downstream sites	
	1993-1997	**1997-2003**	**1993-1997**	**1997-2003**
XS mean elevation	increase	decrease	mostly increase	increase
XS thalweg elevation	increase or no change	decrease	lowering upstream increase downstream	increase
***XS* confinement**	variable	increase or no change	increase	mostly decrease
XS width	increase	increase	no change	mostly no change
XS area	modest increase	great increase	decrease (filling)	modest decrease (filling)
XS volume	slight decrease	great decrease	increase	increase
channel slope	small increase	v. small increase	modest decrease	v. small decrease

Geomorphic impacts of gravel extraction

An important objective of this study was to assess the impact of gravel extraction on the channel of the Mad River. Previous attempts have used sediment budgets (Lehre, 1993, Klein and others 1998, Kondolf and Lutrick 2001) or replenishment estimates from cross-sections (Knuuti and McComas 2003, Fehlman 2004.) Here we attempt to associate gravel extraction qualitatively and quantitatively with observed geomorphic changes.

Our approach involves two stages: 1) an exploratory phase where we graphically investigate time and space relations of extraction and channel geomorphic behavior, and 2) a prediction phase, where we use linear regression to predict quantitative geomorphic response as a function of volume extracted.

Figures 29 and 30 show the time and space patterns of gravel extraction on the Mad River. Since 1993, total yearly gravel extraction has ranged from 135,000 to 236,000 cu. yd.; the 11-year mean is 175,000 cu. yd./year. As Fig 30 makes clear, most gravel is extracted from the upstream reach. From 1993-2003, the upstream reach produced 75% of all gravel extracted from the Mad River. Volumes extracted are available electronically in the *Mad R XSS Data Summary 2003* spreadsheet.

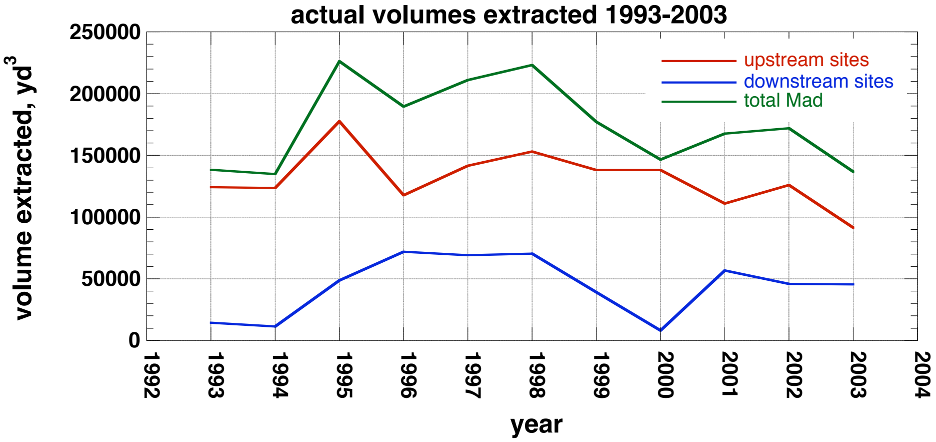

Fig. 29 Volumes of gravel extracted from the Mad River by date, 1993 – 2003.

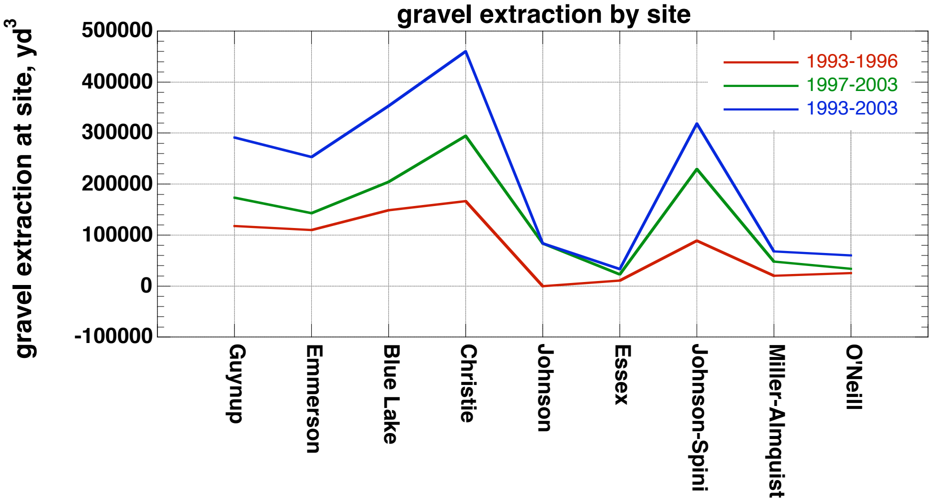

Fig. 30 Volumes of gravel extracted from the Mad River by site, 1993 – 2003.

Effects on XS mean elevation: In Figs. 31A and 31B we plot, by site, volume extracted and change in mean elevation for 1993-96 and 1997-2002 respectively. Note that because gravel is extracted in summer and cross-sections resurveyed the following spring, the effects of volume extracted from 1993-1996 correspond to the 1993-97 elevation change, and the effects of volume extracted from 1997-2002 correspond to the 1997-2003 elevation change.

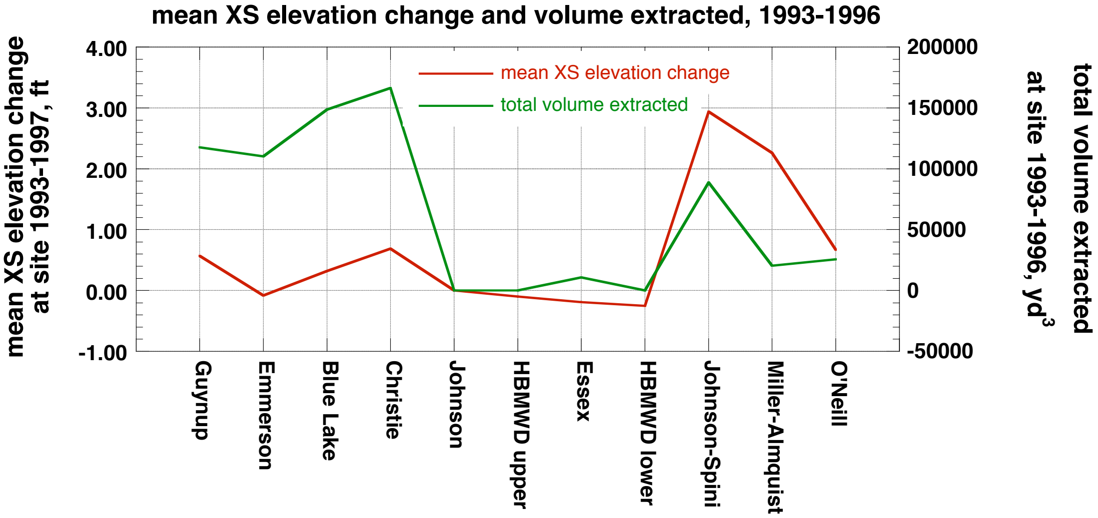

Fig. 31A Variation of mean elevation change and volume extracted by site, 1993-1997.

This graph shows that in both upstream and downstream reaches change in mean elevation has generally paralleled volume extracted, i.e., they have increased and decreased together. Note that because gravel is extracted in summer and cross-sections resurveyed the following spring, the volume extracted from 1993-1996 corresponds with the elevation change from 1993-97

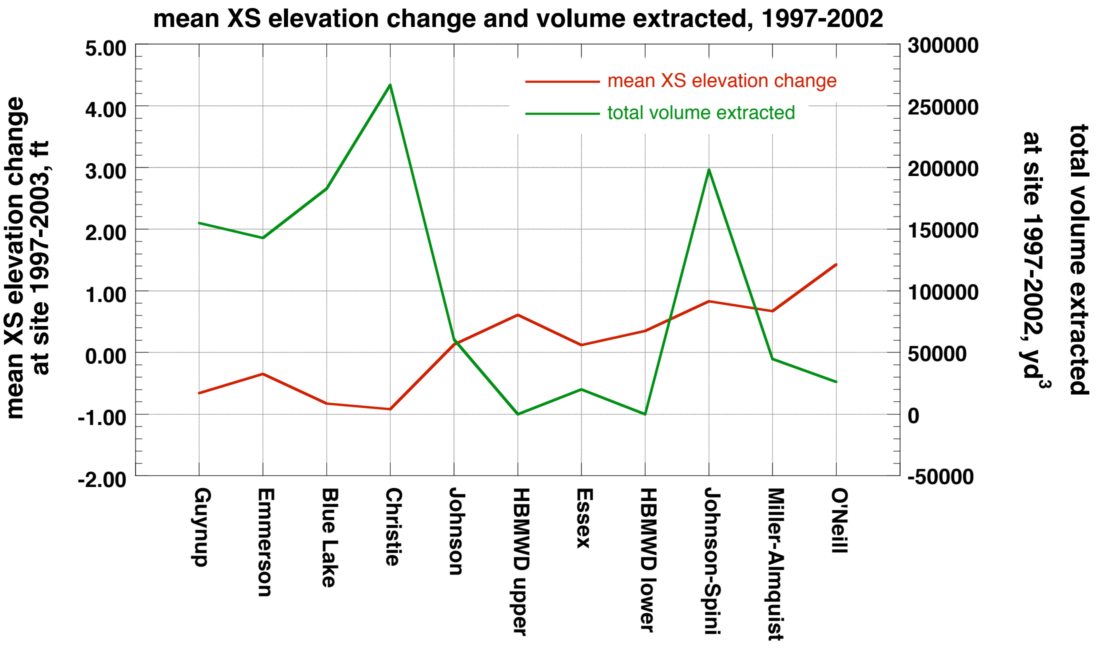

Fig. 31B Variation of mean elevation change and volume extracted by site 1997-2002. This plot shows that at upstream sites change in mean elevation has followed a trend opposite that of volume extracted, but at downstream sites there is no consistent relation between the two.

Inspection of Fig. 31A shows that in both upstream and downstream reaches, 1993-97 change in mean elevation has generally paralleled volume extracted, i.e., they have increased and decreased together. To explore this further, in Fig. 32A we plotted 1993-97 mean elevation change against 1993-96 volume extracted. Both upstream and downstream sites show a crudely linear *increase* in mean elevation with increased extraction. At first glance, this relation is counter-intuitive; one would expect that larger extraction would lead to reduced bar elevation. Instead, increased bar elevations due to significant aggradation in 1994-95 (Fig. 28) allowed increased extraction volumes in 1995 and 1996 (Fig. 29).

For upstream sites, Fig. 31B shows an inverse relation between 1997-2002 volume extracted and 1997-2003 change in mean elevation – increases in extraction were accompanied by decreases in mean elevation and vice versa. For downstream sites, Fig. 31B reveals no consistent pattern.

Fig. 32B reveals a relatively strong ($r^2 = 0.85$) inverse linear relation between 1997-2002 volume extracted and 1997-2003 change in mean elevation at upstream sites. No such relation exists for the downstream sites.

The decrease of mean elevation with increasing extraction at upstream sites in Fig. 32B is what one would logically expect. The upstream bars aggraded in 1997-1998 and have been relatively steadily losing volume ever since (Fig. 28) At the same time upstream extraction peaked in 1998 and has been gradually declining since then, tracking the decline in volume (Fig. 29). This suggests that the inverse relation between mean elevation and extraction is not merely an artifact of the amount of extraction permitted, but may have predictive value.

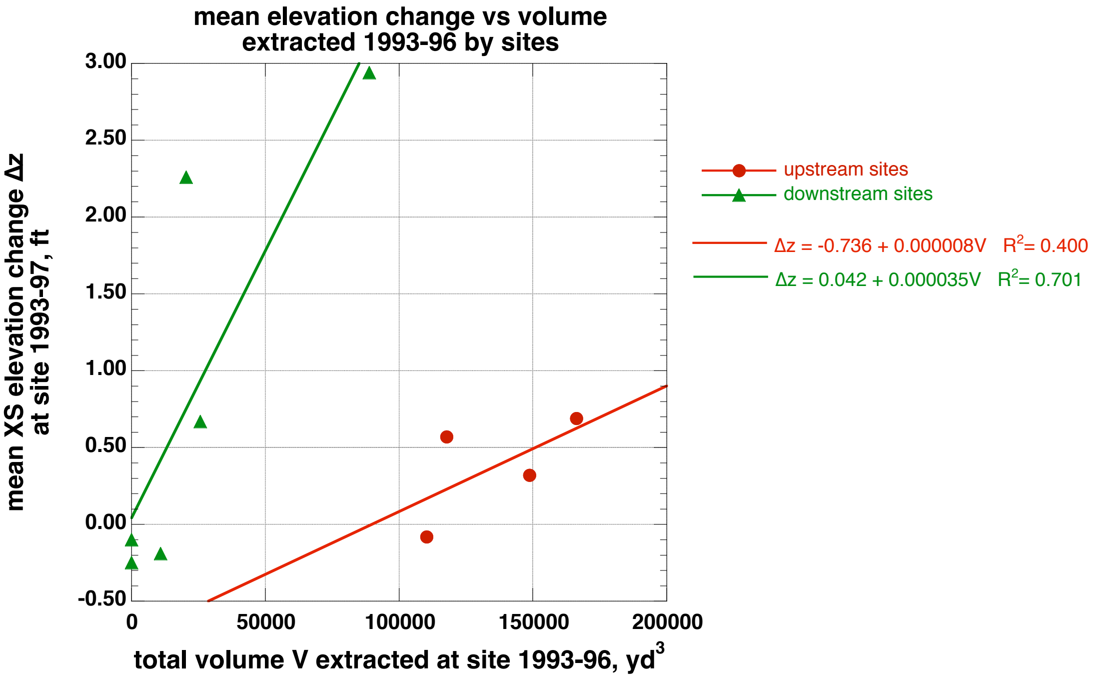

Fig. 32A Relation between mean elevation change and volume extracted, 1993-1996.
This plot reveals weak positive linear relations between volume extracted and change in mean elevation at both upstream and downstream sites. The relation is stronger for downstream sites (r^2 = 0.70) than upstream ones (r^2 = 0.40).

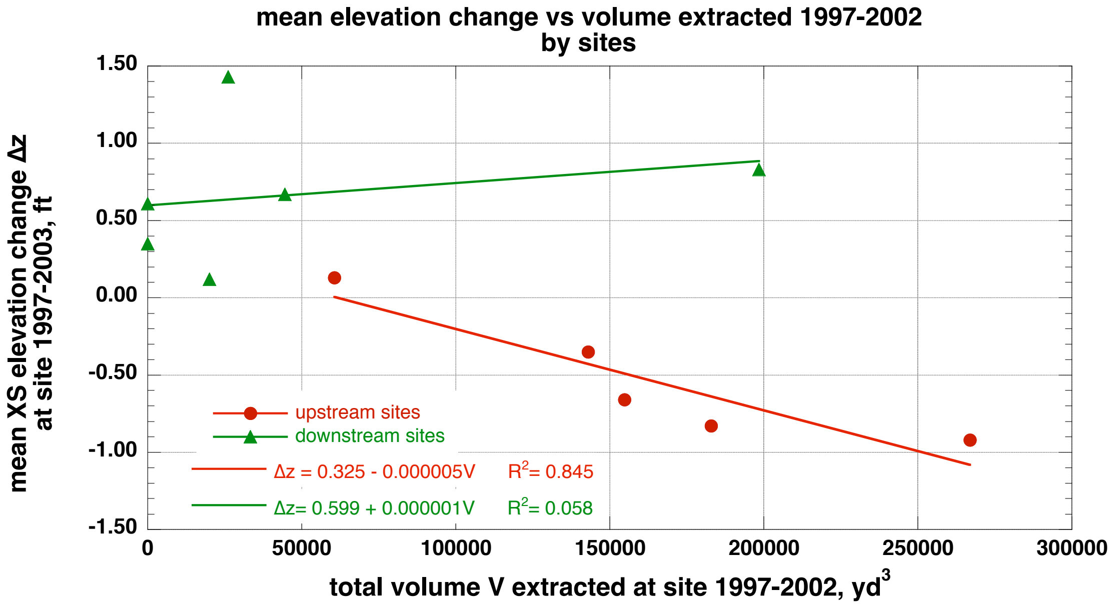

Fig. 32B Relation between mean elevation change and volume extracted, 1997-2002.
This plot reveals a relatively strong (r^2 = 0.85) inverse linear relation between mean elevation change at upstream sites and volume extracted. No relationship exists between extraction and elevation change for downstream sites.

Effects on mean thalweg elevation: In Figs. 33A and 33B we plot, by site, volume extracted and change in mean thalweg elevation for 1993-96 and 1997-2002 respectively. The pattern in these plots is similar to that described above for mean elevation, since thalweg elevation tends to track mean elevation.

Figs. 34A and 34B are linear regressions of change in mean thalweg elevation on volume extracted. For upstream sites there is no relation between thalweg elevation change and 1993-96 volume extracted, and a moderate (r^2 = 0.73) inverse linear relation for 1997-2002. For downstream sites, a weak (r^2 = 0.50) positive linear relation exists between thalweg elevation change and 1993-96 extraction volume, but there is no reliable relation for 1997-2002 (Fig. 34B).

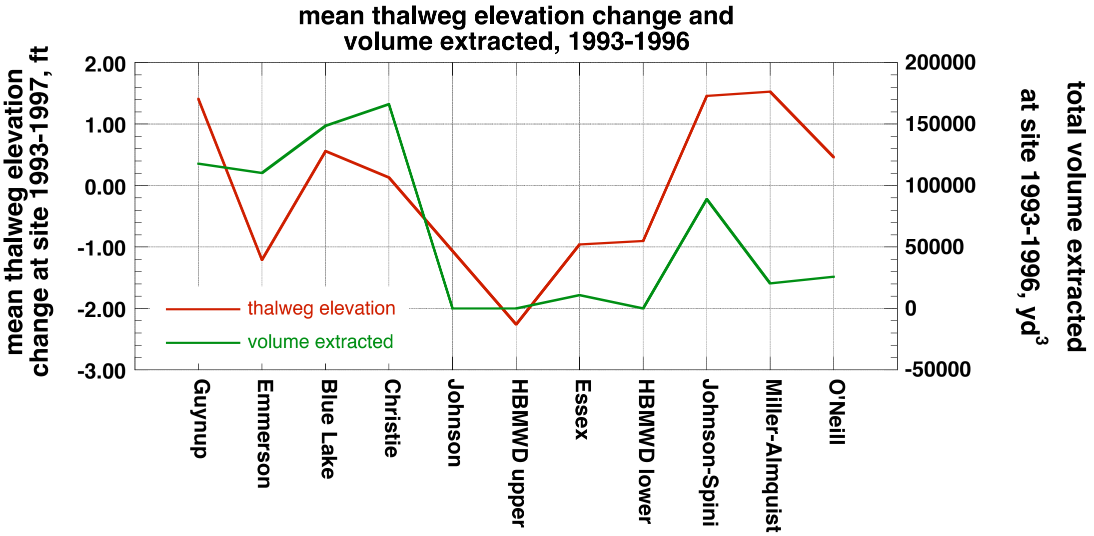

Fig. 33A Variation of mean thalweg elevation change and volume extracted by site, 1993-1996. This graph shows that in both upstream and downstream reaches change in mean thalweg elevation has generally paralleled volume extracted. This pattern is similar to that for mean elevation in Fig. 31A.

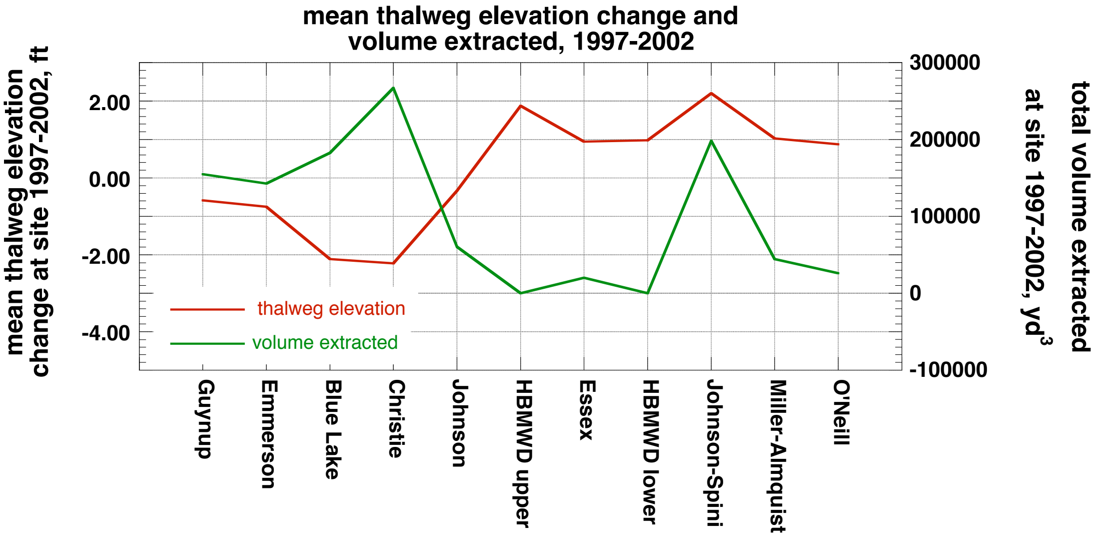

Fig. 33B Variation of mean thalweg elevation change and volume extracted by site, 1997-2002. This plot shows that at upstream sites change in mean elevation has followed a trend opposite that of volume extracted, but at downstream sites there is no consistent relation between the two. This pattern is similar to that for mean elevation in Fig. 31B.

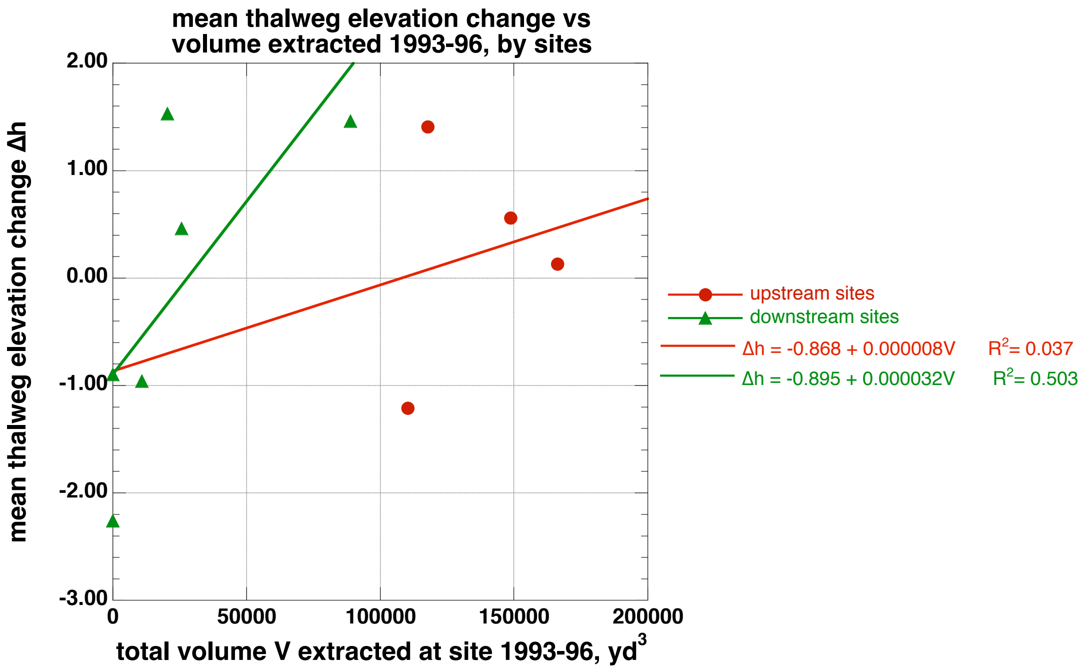

Fig. 34A Relation between mean thalweg elevation change and volume extracted, 1993-1996. This plot exhibits a weak positive linear relation between volume extracted and change in mean thalweg elevation at downstream sites. There is no relation between them at upstream sites.

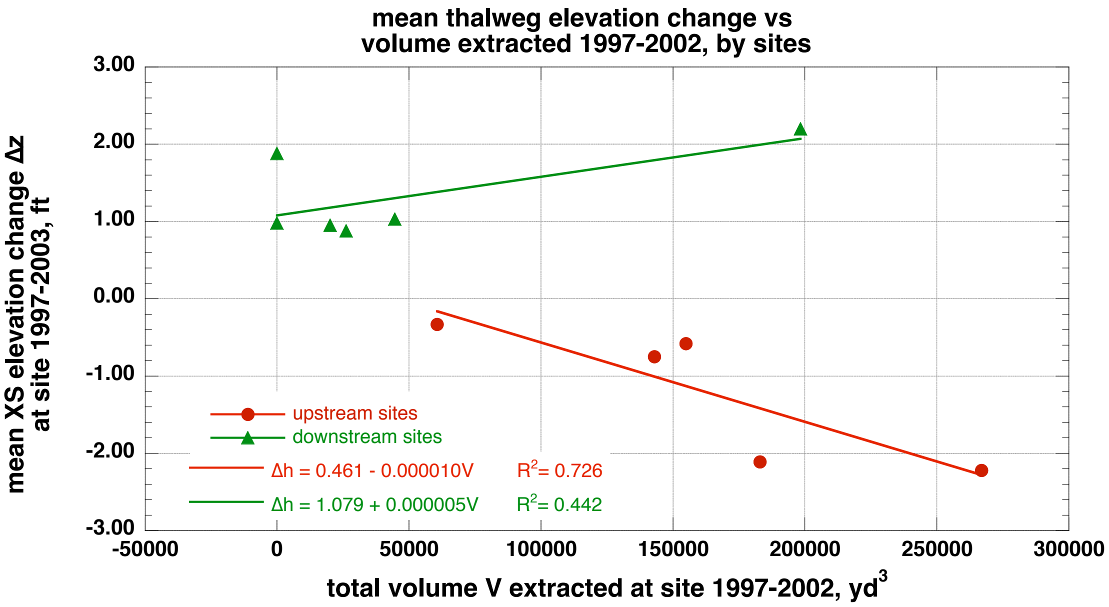

Fig. 34B Relation between mean thalweg elevation change and volume extracted, 1997-2002. For 1997-2002 this plot reveals a moderate (r^2 = 0.73) inverse linear relation between mean thalweg elevation change at upstream sites and volume extracted. No meaningful relationship exists between extraction and thalweg elevation change for downstream sites because the slope of the regression line is controlled almost entirely by the rightmost point.

Effects on mean confinement: Figures 35A and 35B show volume extracted and mean confinement change by site. For 1993-96 (Fig. 35A) no relation between confinement change and volume extracted is evident for either upstream or downstream reaches. For 1997-2002, confinement change crudely parallels volume extracted down as far as Essex Bar, but farther downstream confinement change moves opposite to volume change. As expected, linear regressions of confinement change on volume extracted bear out this lack of relation: the strongest relation (for upstream sites, 1997-2002) only has $r^2 = 0.35$; all the others have $r^2 < 0.15$. Clearly there is little quantitative relation between confinement changes and amount of gravel extracted.

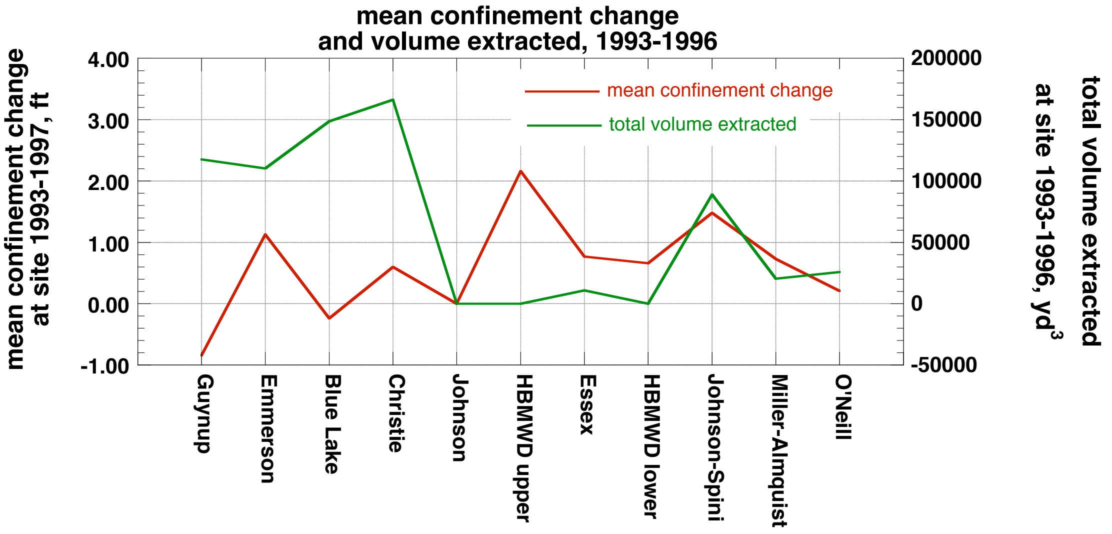

Fig. 35A Variation by site of mean confinement change and volume extracted, 1993-1996.
For this period there does not appear to be any consistent relation between mean confinement change and volume extracted at either upstream or downstream sites.

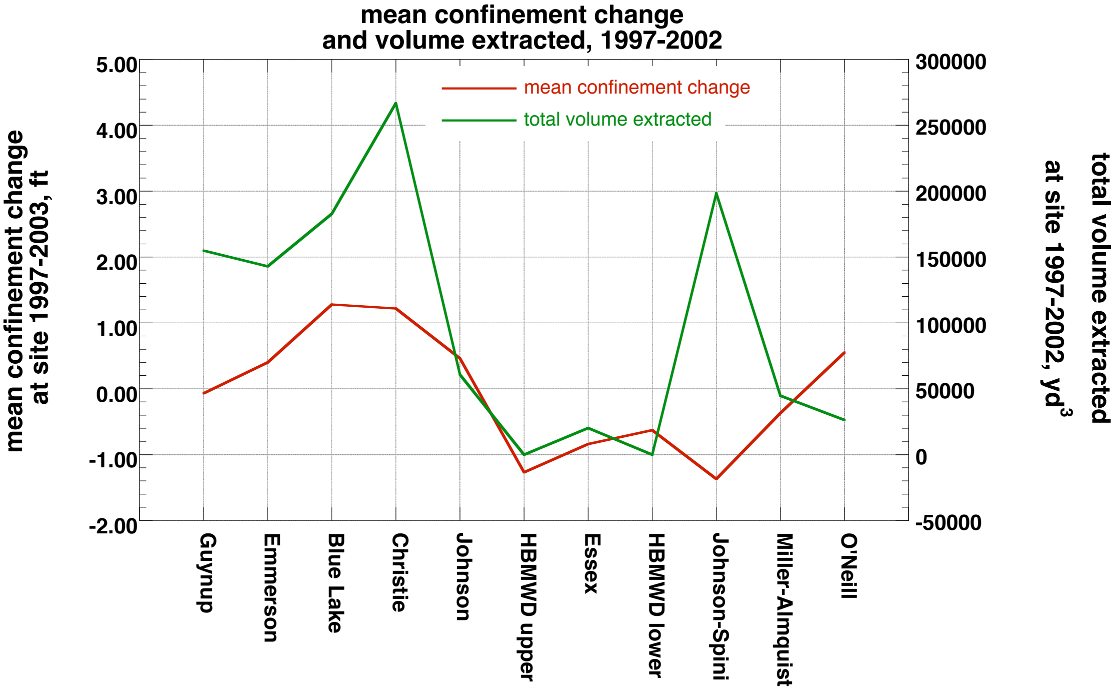

Fig. 35B. Variation by site of mean confinement change and volume extracted 1997-2002.
At upstream sites, and downstream to Essex Bar, confinement changes crudely parallel volume extracted. Below Essex Bar, confinement changes move opposite to extracted volume.

Effects on mean XS width: Figures 36A and 36B are plots of volume extracted and mean XS width change by site. Inspection of Fig 36A (1993-96) reveals no consistent relation between mean width change and volume extracted at either upstream or downstream sites. In Fig. 36B (1997-2002), mean width change strongly parallels volume extracted at upstream sites, i.e., greater extraction volumes are accompanied by greater increases in width. In the downstream reach the relation is weak because cross-section width stays nearly constant, regardless of volume extracted.

Figs. 37A and 37B are linear regressions of change in mean width on volume extracted. For 1993-96 (Fig. 37A) there is no relation between volume extracted and change in mean XS width at upstream sites; while the relation for downstream sites is suspect (despite its $r^2 = 0.78$) because the position of the regression line depends almost entirely on the rightmost point. Fig. 37B shows a relatively strong ($r^2 = 0.88$) positive linear relation between change in mean width at upstream sites and volume extracted. This is consistent with what one would logically expect. The relation for downstream sites is suspect because the position of the regression line again depends almost entirely on the largest point; were it omitted, the relation would be a horizontal line.

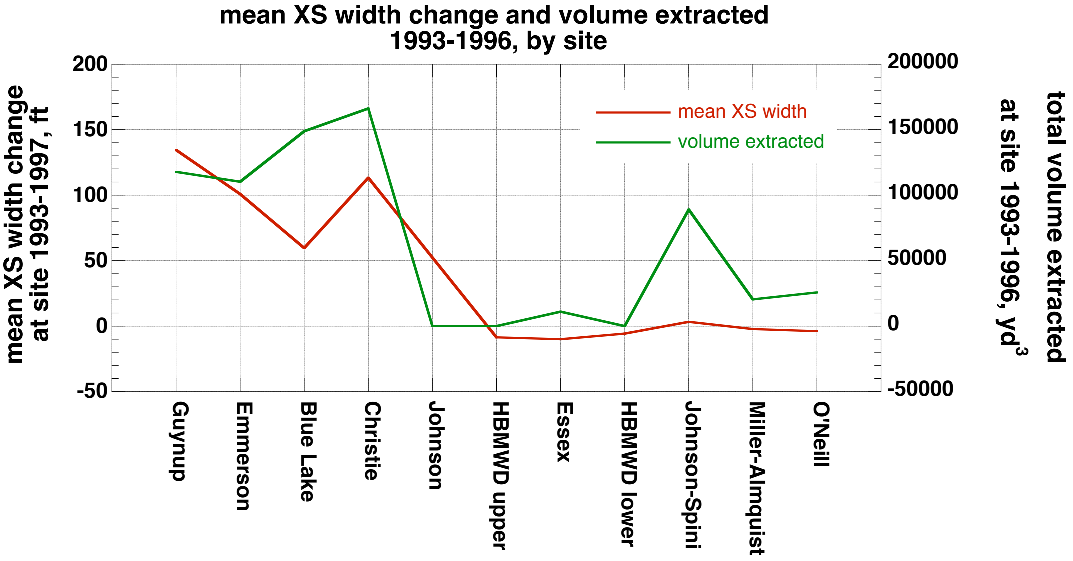

Fig. 36A Variation by site of mean XS width change and volume extracted, 1993-1996.
For this period there does not appear to be any consistent relation between mean XS width change and volume extracted at either upstream or downstream sites.

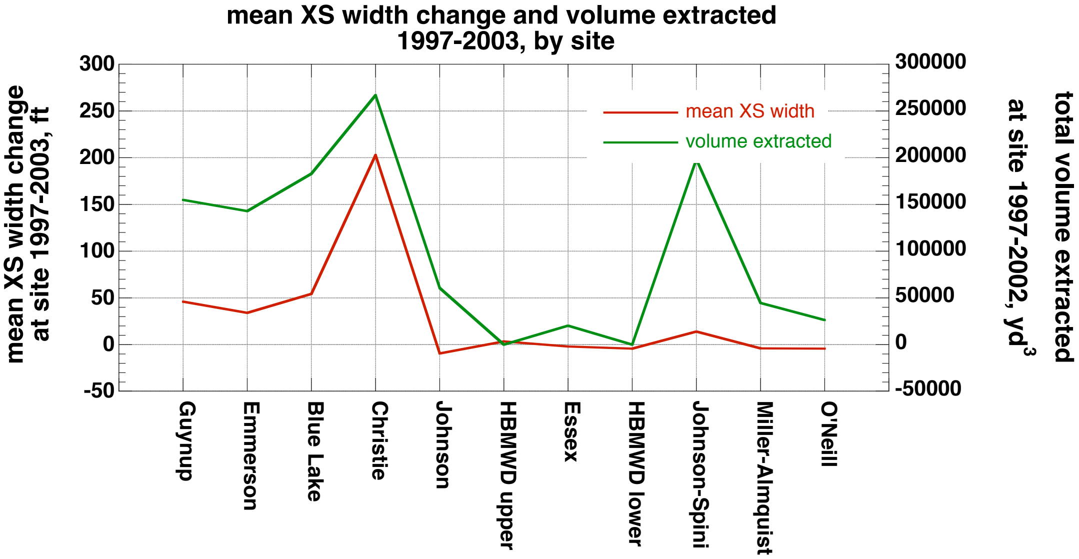

Fig. 36B Variation by site of mean XS width change and volume extracted 1997-2002.
At upstream sites mean width change strongly parallels volume extracted. In the downstream reach the relation is weak because XS width stays nearly constant.

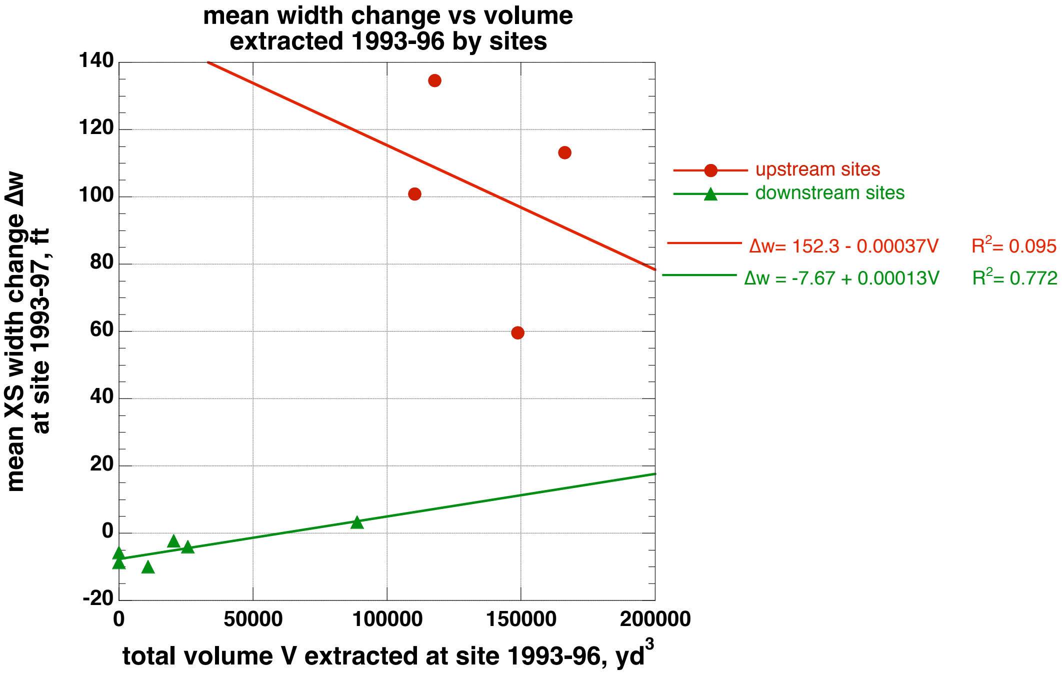

Fig. 37A Relation between mean XS width change and volume extracted, 1993-1996. This plot indicates no relation between volume extracted and change in mean XS width for upstream sites; the relation for downstream sites is suspect because the position of the regression line depends almost entirely on the largest point.

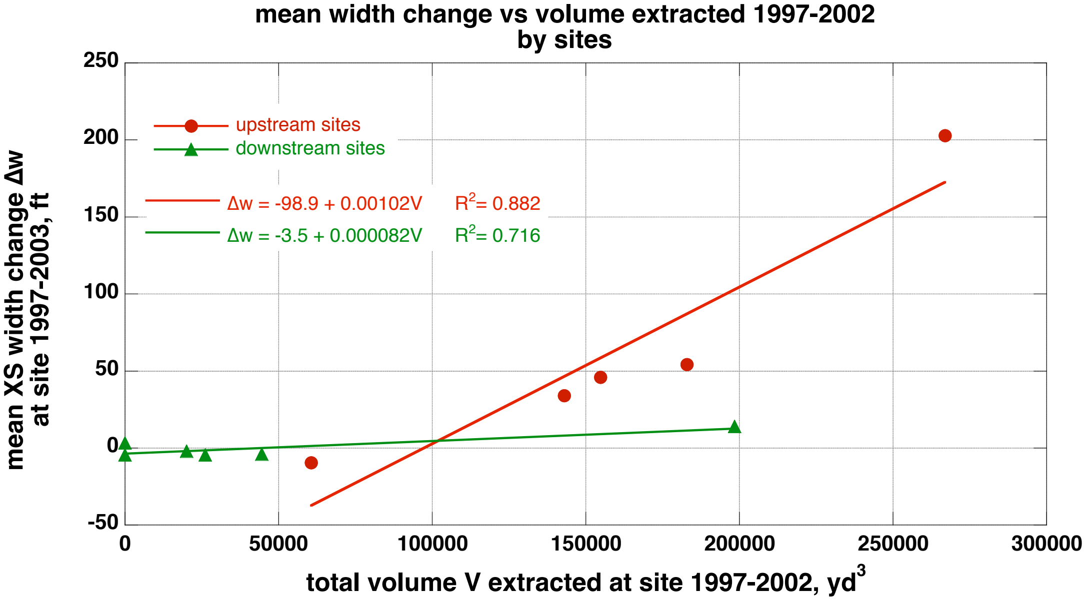

Fig. 37B Relation between mean XS width change and volume extracted, 1997-2002. This plot reveals a relatively strong (r^2 = 0.88) positive linear relation between change in mean width at upstream sites and volume extracted. The relation for downstream sites is suspect because the position of the regression line depends almost entirely on the largest point; if it were omitted, the relation would be a horizontal line.

Effects on mean XS area: Figures 38A and 38B show mean XS area change and volume extracted by site. For 1993-96 changes in cross-section area at both upstream and downstream sites followed a trend opposite that of volume extracted: increases in extraction are accompanied by smaller change in cross-section area, and vice versa (Fig. 38A). For 1997-2002, changes in cross-section area closely parallel volume extracted as far downstream as the lower HBMWD site (Fig. 38B); farther downstream there is little relation between the two.

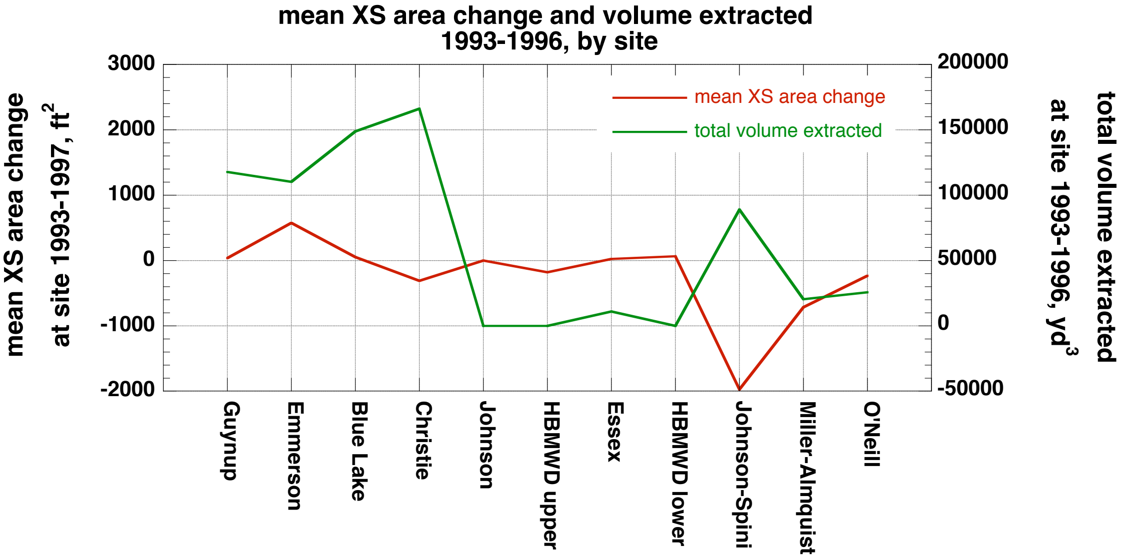

Fig. 38A Variation by site of mean cross-section area change and volume extracted, 1993-1996. For 1993-1996, at both upstream and downstream sites changes in cross-section area have followed a trend opposite that of volume extracted: increases in extraction are accompanied by reductions in cross-section area, and vice versa. Negative values indicate filling.

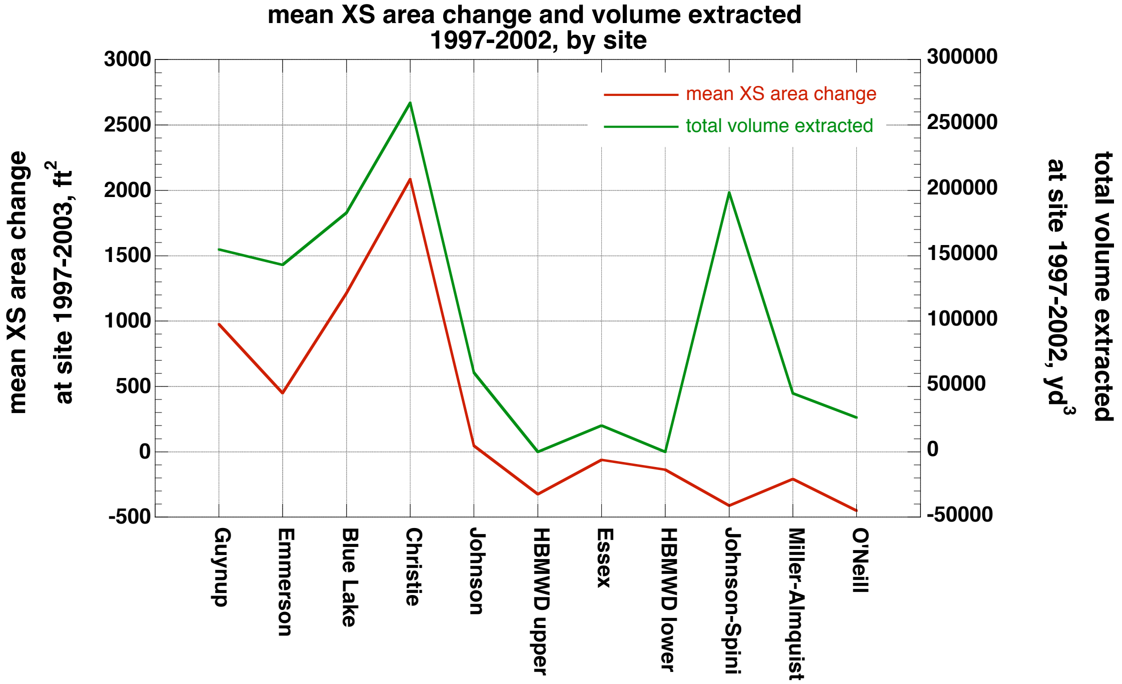

Fig. 38B Variation by site of mean cross-section area change and volume extracted, 1997-2002. For 1997-2002, changes in cross-section area closely parallel volume extracted downstream as far as the lower HBMWD site. Farther downstream there is little relation between area change and amount extracted. Negative values indicate filling.

Figures 39A and 39B display linear regressions of mean XS area change on volume extracted. Fig. 39A shows inverse linear relations between volume extracted and change in mean XS area at both upstream and downstream sites for the 1993-1996 period. The upstream relation is moderate ($r^2 = 0.71$), while the downstream relation is not as strong as it appears (even though $r^2 = 0.91$) because the line position depends mostly on the single rightmost point.

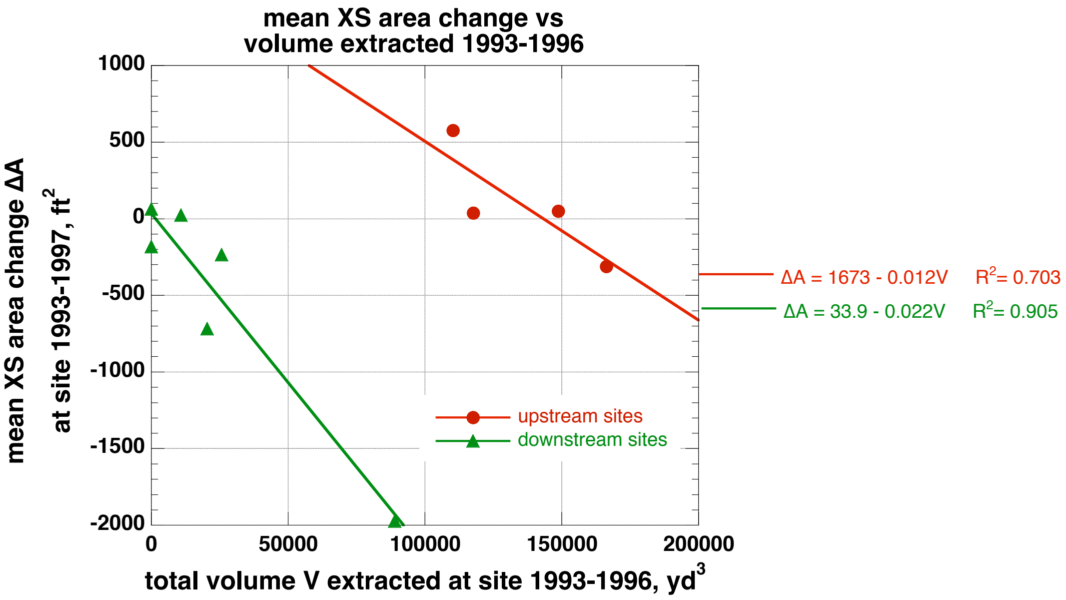

Fig. 39A Relation at sites between mean cross-section area change and volume extracted 1993-1996. This plot shows inverse linear relations between volume extracted and change in mean XS area at both upstream and downstream sites for the 1993-1996 period. The relation for downstream sites is not as strong as it appears because the position of the line depends greatly on the rightmost point.

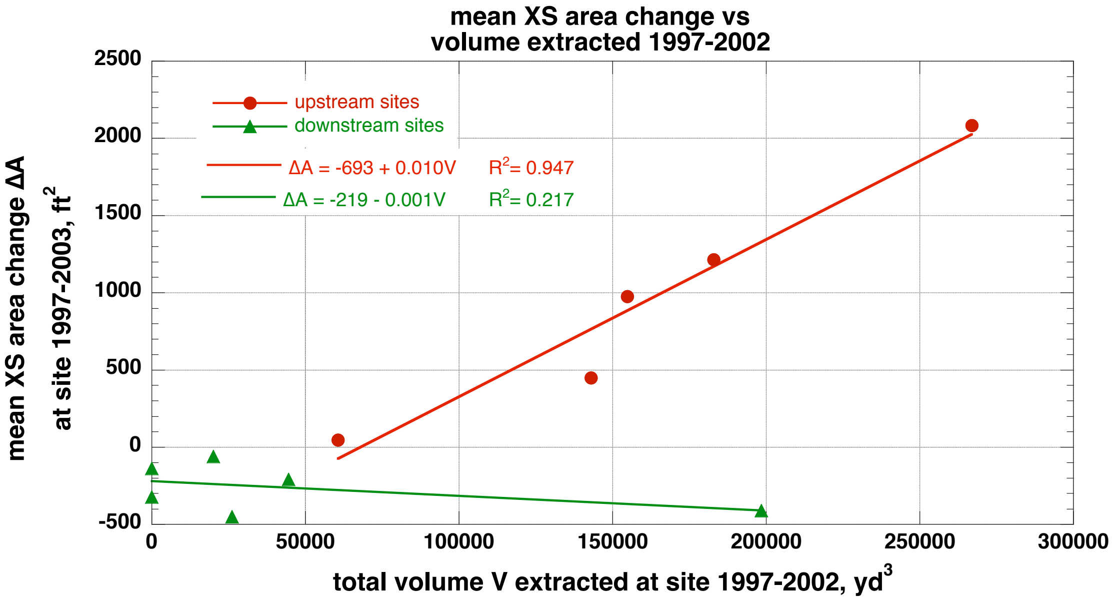

Fig. 39B Relation at sites between mean cross-section area change and volume extracted 1997-2002. For 1997-2002, the plot indicates a strong ($r^2 = 0.95$) positive linear relation between change in mean XS area at upstream sites and volume extracted. The relation for downstream sites is not meaningful because the position of the regression line depends almost entirely on the largest point; if it were omitted, the relation would be a horizontal line. Mean area change appears independent of volume extracted at downstream sites.

For 1997-2002, Fig. 39B indicates a strong ($r^2 = 0.95$) positive linear relation between change in mean XS area at upstream sites and volume extracted. The relation for downstream sites is not meaningful because the position of the regression line depends almost entirely on the largest point; were it omitted, the relation would be a horizontal line. Thus mean area change appears independent of volume extracted at downstream sites.

The inverse relations (Fig. 39A) observed between XS area change and extraction volume in 1993-96 are troubling, especially in the upstream reach. Logically, one would expect that as more gravel is extracted, cross-sectional area would increase, not decrease, yet just the opposite was observed. We hypothesize that the significant aggradation which occurred in 1994-95 decreased cross-section area by raising mean elevation (Fig. 31A), while at the same time allowing larger amounts of extraction. Subsequently, the more extensive extraction may have facilitated trapping of material redistributed from upstream, slowing the increase of cross-section area.

The strong positive relation between area change and volume extracted (Fig. 39B) is what one would expect if a causal relation exists between the two. Following additional aggradation in 1997-98, sediment input from upstream has been relatively modest (see Fig. 44) and mining and the river have been removing material from storage (Fig. 27). This would lead to cross-section area increasing in step with the volume of gravel extracted. The lack of relation in the downstream reach reflects its persistent aggradation.

Effects on channel volume: Figures 40A and 40B are plots of volume extracted and change in channel volume by site. For 1993-1996, change in channel volume has followed a weak trend opposite that of volume extracted at both upstream and downstream sites : increases in extraction are accompanied by reductions in channel volume, and vice versa (Fig. 40A). For 1997-2002, changes in channel volume follow the same trend as volume extracted as far downstream as the lower HBMWD site (Fig. 40B). Farther downstream there is little relation between channel volume change and volume extracted.

In Fig. 41 we plot 1993-2002 cumulative volume extracted and cumulative net volume change against downstream position by site. For the reach containing the four large upstream bars, cumulative net volume change and cumulative volume extracted almost exactly parallel each other, suggesting a strong positive relation between the two. Downstream from Christie Bar, the cumulative net volume change steadily declines due to aggradation, while cumulative volume extracted continues to increase.

Figures 42A – 42C are linear regressions of channel volume change on volume extracted for 1993-96, 1997-2002, and 1993-2002 respectively. Fig. 42A shows inverse linear relations between volume extracted and change in net channel volume at both upstream and downstream sites for the 1993-1996 period. Both relations have moderate predictive value ($r^2 = 0.69$ and 0.73), but the downstream relation is not as strong as it appears because the line position depends mostly on the single rightmost point. (If this one point is removed, there is no relation.)

For 1997-2003 and 1993-2003, Figs. 42B and 42C exhibit a strong ($r^2 = 0.90$ and 0.93) positive linear relation in the upstream reach between channel volume change and volume extracted. Volume change is independent of extraction in the downstream reach: the slope of the line is not statistically different from horizontal in either plot.

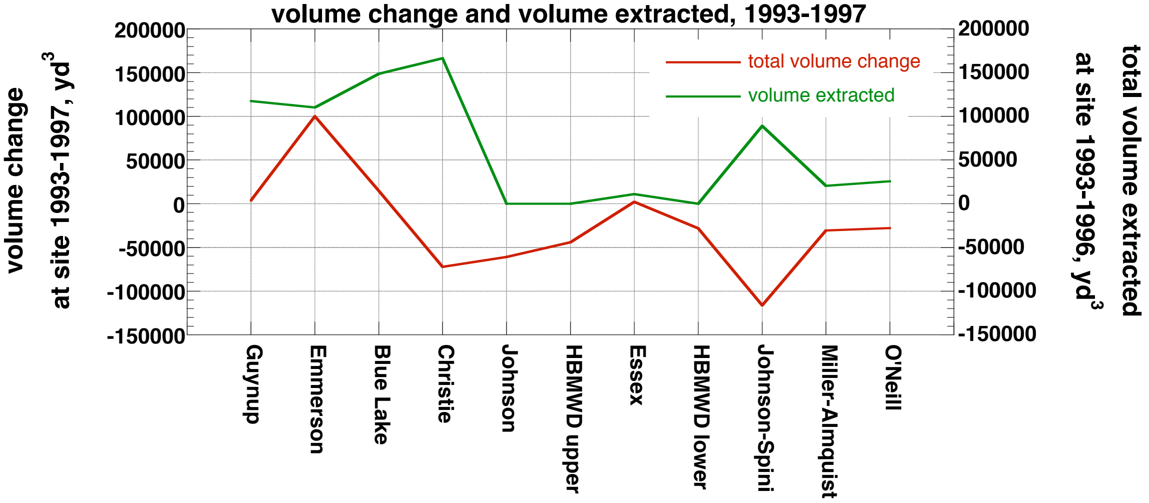

Fig. 40A Variation by site of channel volume change and volume extracted, 1993-1996.
For 1993-1996, at both upstream and downstream sites changes in channel volume have followed a weak trend opposite that of volume extracted: increases in extraction are accompanied by reductions in channel volume, and vice versa. Negative values indicate filing.

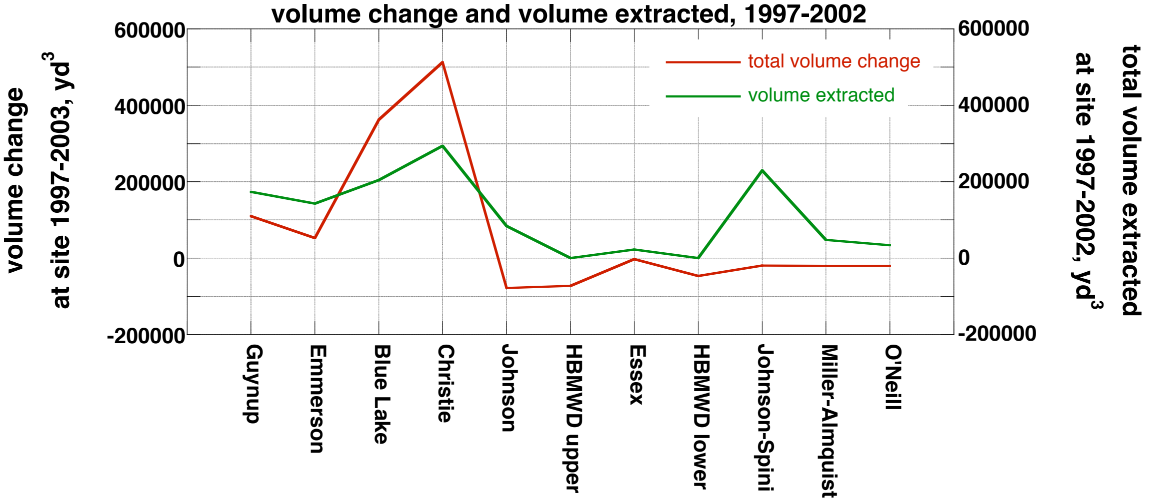

Fig. 40B Variation by site of channel volume change and volume extracted, 1997-2002.
For 1997-2002, changes in channel volume follow the same trend as volume extracted downstream as far as the lower HBMWD site. Farther downstream there is little relation between volume change and volume extracted. Negative values indicate filling.

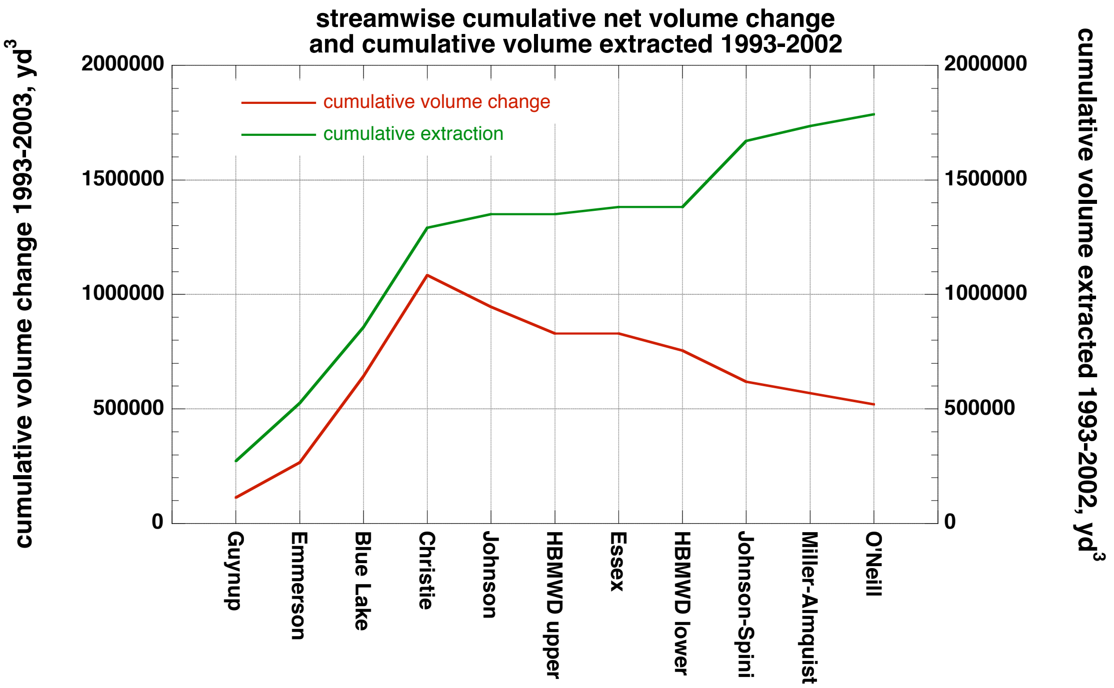

Fig. 41 Downstream cumulative net volume change and cumulative volume extracted, 1993-2002
For the reach containing the four large upstream bars, cumulative net volume change and cumulative volume extracted almost exactly parallel each other, suggesting a strong positive relation between the two. Downstream from Christie Bar, the cumulative net volume change steadily declines due to aggradation, while cumulative volume extracted continues to increase.

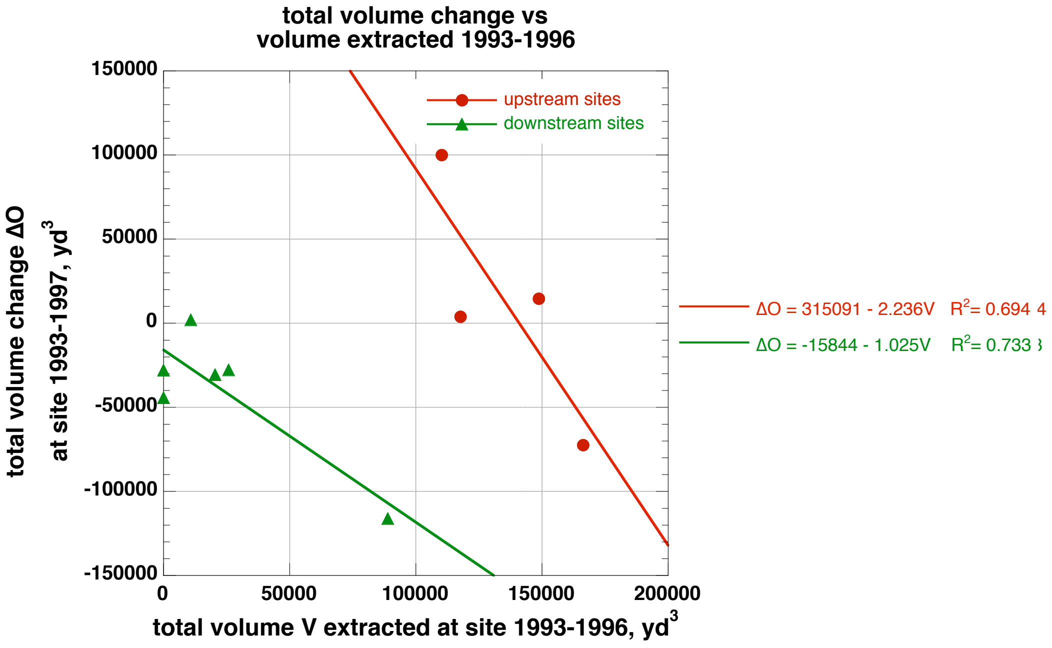

Fig. 42A Relation at sites between channel volume change and volume extracted 1993-1996
This plot shows inverse linear relations between volume extracted and change channel volume at both upstream and downstream sites for the 1993-1996 period. The relation for downstream sites is not as strong as it appears because the position of the line depends greatly on the rightmost point.

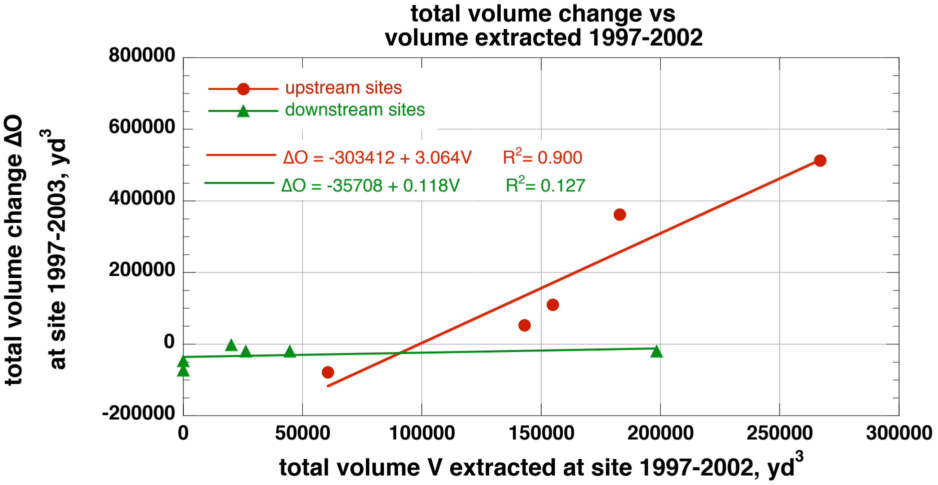

Fig. 42B Relation at sites between channel volume change and volume extracted 1997-2002

For 1997-2002, the plot indicates a fairly strong (r^2 = 0.90) positive linear relation between change in volume at upstream sites and volume extracted. The relation for downstream sites is not meaningful because 1) the line is nearly horizontal, and 2) the position of the regression line depends almost entirely on the largest point. Channel volume change appears independent of volume extracted at downstream sites.

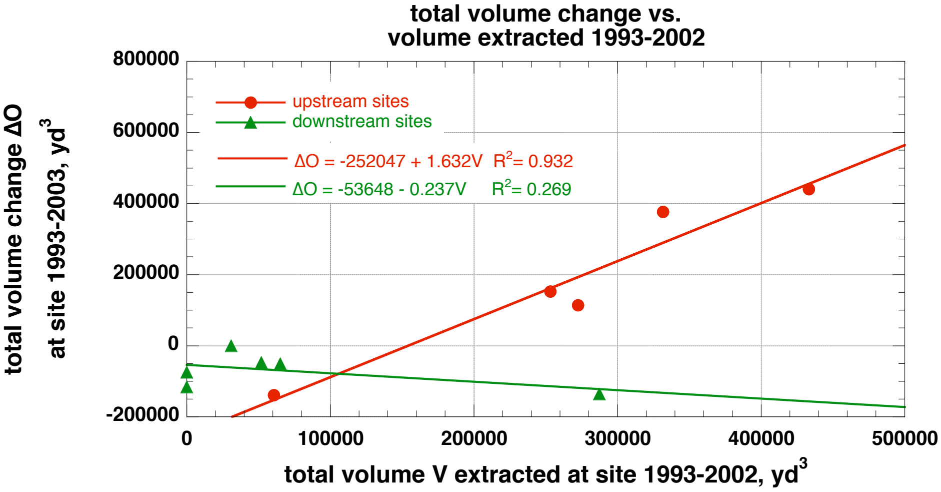

Fig. 42C Relation at sites between channel volume change and volume extracted 1993-2002

For 1993-2002, the plot indicates a strong (r^2 = 0.93) positive linear relation at upstream sites between change in channel volume and volume extracted. The relation for downstream sites is not meaningful because the position of the regression line depends almost entirely on the largest point; if it were omitted, the relation would be a horizontal line. Channel volume change appears nearly independent of volume extracted at downstream sites.

We interpret the 1993-96 inverse relation between extraction and volume change (Fig. 42A) the same as we did above for area: the significant aggradation which occurred in 1994-95 reduced channel volume by raising mean elevation (Fig. 31A), while simultaneously allowing larger extraction volumes. Subsequently, the more extensive extraction probably facilitated trapping of material redistributed from upstream, reducing increase in channel volume.

Strong positive relations between volume change and volume extracted (Figs. 42A-B) are what one would expect if a causal relation exists. Following additional aggradation in 1997-98, sediment input from upstream has been relatively modest (see Fig. 44) and mining and the river have been removing material from storage (Fig. 27). As with cross-section area, this would lead to channel volume increasing in step with volume of gravel extracted. The lack of relation in the downstream reach reflects its persistent aggradation.

Effects of repeated extraction: One might hypothesize that cross-sections experiencing repeated extraction have different geomorphic response than those which have had little or no extraction. In Fig. 39, we plot, for upstream cross-sections, 1997-2003 changes in XS mean elevation, XS width, XS area, and channel volume against number of years with extraction. No relation is apparent in any of these plots, and we conclude that repeated extraction produces no unique effects.

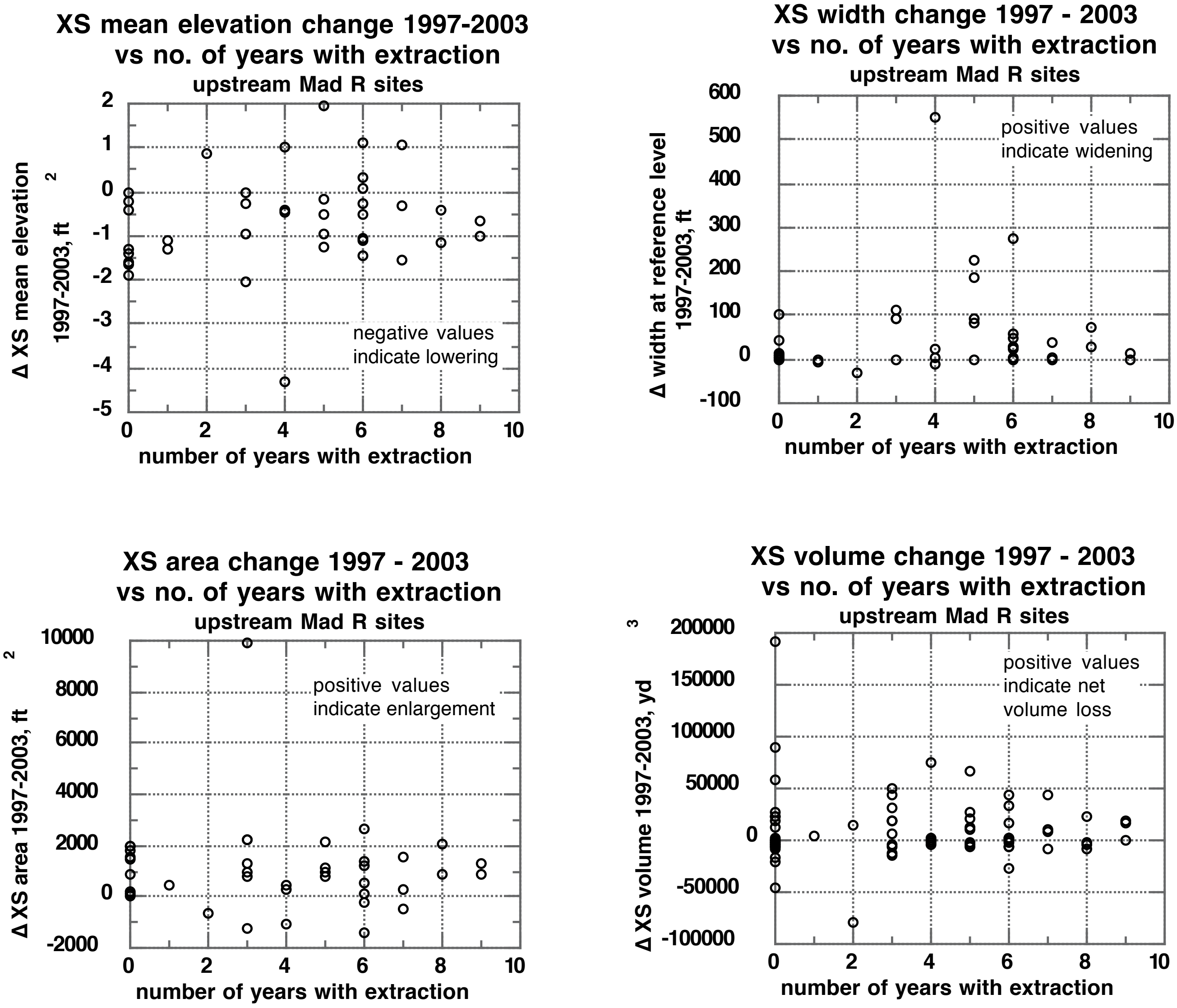

Fig. 43 Relation number of years cross-sections experienced extraction and changes in geomorphic properties at upstream sites

These plots show that for upstream sites there is no relation between how often a cross-section experienced extraction and the size of changes in XS mean elevation, XS width, XS area, or volume. Frequency of extraction appears to have no systematic relation to changes in cross section properties.

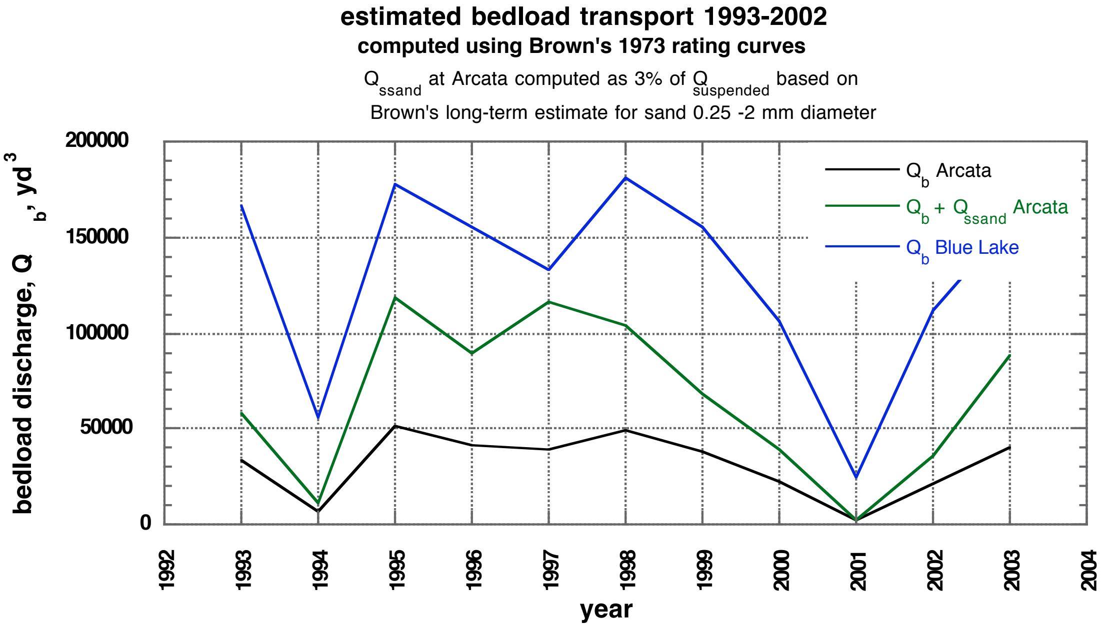

Fig. 44 Estimated bedload transport by year, 1993-2002.
A density of 1.55 tons/cu. yd. was used to convert tonnages

Summary of geomorphic impacts of gravel extraction

In Table 13, we summarize the relations we observe between volume of gravel extracted and geomorphic response. For the upstream reach, significant aggradation in 1994-95 raised bed and bar elevations and allowed for larger-than-average extraction in 1993-96; the result is that increases in extraction were associated with increases in XS mean elevation and decreases in mean XS area and channel volume. It should be emphasized that these are *not* causal relations: the observed pattern reflects the response of both the river and the miners (and their permitting agencies) to a large influx of sediment. No relation was found between extraction volume and changes in mean thalweg elevation, mean confinement, or mean cross-section width.

For 1997-2002 and 1993-2002, the upstream reach exhibits strong positive linear relations between volume extracted and changes in mean width, mean XS area, channel volume, and a strong negative linear relation with mean XS elevation. That is, increases in volume extracted are associated with increasing channel width, XS area, and volume, and with decreasing mean XS and (more weakly) thalweg elevation. Confinement change shows no relation to volume extracted.

In the downstream reach, no significant relations exist between volume extracted and change in any of the geomorphic variables, presumably because of the persistent post-1993 aggradation.

Table 13 -- Summary of Mad River relations between gravel extraction and geomorphic response, 1993-2003

	upstream sites		downstream sites	
	1993-1997	**1997-2003**	**1993-1997**	**1997-2003**
XS mean elevation	increase with increasing extraction; weak relation	decrease with increasing extraction; mod. strong relation	increase with increasing extraction; moderate relation	no relation
XS thalweg elevation	no relation	decrease with increasing extraction; moderate relation	increase with increasing extraction; weak relation	no relation
XS confinement	no relation	no relation	no relation	no relation
XS width	no relation	increase with increasing extraction; rel. strong relation	slight increase with increasing extraction; relation suspect	probably no relation
XS area	decrease with increasing extraction; moderate relation	increase with increasing extraction; strong relation	decrease with increasing extraction; moderate relation	no relation
XS volume	decrease with increasing extraction; moderate relation	increase with increasing extraction; strong relation	decrease with increasing extraction; relation suspect	no relation

Implications for extraction volume or "safe yield"

We believe that the geomorphic analysis in the preceding section provides tools for assessing the potential impact of gravel extraction on mean channel geomorphology, and a means for estimating the average amount of gravel that might be extracted annually without undesired geomorphic consequences, i.e., "safe yield". Our approach is outlined below.

Estimation of "zero-effect" extraction volume for the upstream reach

The strength of the 1997-2002 and 1993-2002 upstream mean elevation, width, XS area, and channel volume regressions (all have $r^2 \geq 0.85$), together with the even distribution of points along the regression lines suggest that these relations have real predictive power *under present or long-term average conditions* in the upstream reach. Specifically, as long as the reach experiences, on the average, small to moderate influx of sediment from upstream, and small to moderate volumes of extraction, we can use the regressions to predict geomorphic response to increased or decreased extraction levels. On the other hand, major aggradation and/or channel reorganization -- such as might be caused by a 20-year or larger flood – can reset the relation and create a less-predictable state. Greatly increased extraction of gravel from the reach is also likely to create a different set of relations. Unless there is a sound physical or theoretical basis, regression equations should not be applied to conditions lying greatly outside the range of data used in their creation.

To estimate a "zero-effect" extraction volume for the upstream reach, we set the regression equations for mean XS elevation change, mean width change, mean XS area change, and mean channel volume change each equal to zero (i.e., no change) and solved for the corresponding per-site extraction volume. Dividing this by the number of years the regression spans yield the annual per-site "zero-effect" volume. Multiplying these estimates by 5 (the number of upstream sites) yields the annual "zero-effect" volume for the entire upstream reach. Our estimates and the equations used are given in Table 14 below.

Table 14 -- Estimates of "zero-effect" volume from regression equations

				annual "zero-effect" volume cu. yd.	
variable	equation	years spanned	no years	per site	reach
XS mean elevation	$\Delta z = 0.325 - 0.000005V$	1997-2002	6	10200	51000
XS width	$\Delta w = -98.9 + 0.00102V$	1997-2002	6	16200	81000
XS area	$\Delta A = -693 + 0.010V$	1997-2002	6	11300	56500
channel volume	$\Delta O = -303412 + 3.064V$	1997-2002	6	16500	82500
channel volume	$\Delta O = -252047 + 1.632V$	1993-2002	10	15400	77000

This analysis suggests that an annual mean extraction rate of about 55,000 – 85,000 yd^3/year from the upstream reach should have minimal effect on channel enlargement under current conditions. Actual extraction from this reach has averaged 135,000 yd^3/year.

We would like to emphasize that we are not recommending here that upstream extraction be reduced to this "zero-effect" amount. Regression equations have inherent uncertainty (scatter about the line) which creates error in the estimates; this error could easily be on the order of 20 –30% or more. In addition, the regression relations do not predict changes at individual cross-sections or specific individual sites; they predict *mean* change for an *average* site. They do suggest, however, that the upstream reach cannot support extraction in excess of the current amount without undesired effects, and that it might be prudent to manage the upstream reach, if possible, for smaller volume.

We point out here that channel enlargement by widening/bank erosion must at some point encounter natural limits as the material of the lower terraces – especially those created by deposition in the 1955 and 1965 floods-- is consumed. At that point the channel can enlarge only by cutting down.

Estimation of "zero-effect" extraction volume for the downstream reach

As stated earlier, the downstream reach has undergone persistent deposition since 1993, and there are no meaningful relations between volume extracted and changes in geomorphic properties. Instead, we approach this by observing that from 1993-2002 the downstream reach has experienced 1) mean yearly extraction of 44,000 yd^3/year and 2) mean yearly net deposition (volume increase) of 42,000 yd^3/year. For the 1997-2002 period these volumes are 48,000 yd^3/year and 30,000 yd^3/year respectively. Thus under current conditions *at least* 45,000 – 50,000 yd^3/year can be extracted and still have net deposition of 30,000 – 40,000 yd^3/year. This suggests that it might be possible to increase extraction in the downstream reach without undesirable consequences. An increase in extraction equal to half the mean net deposition – i.e., of 15,000-20,000 yd^3/year -- does not seem unreasonable if it is balanced by reductions in extractions from the upstream reach. It would still allow annual mean net aggradation of 15,000 – 20,000 yd^3/year, which would presumably limit undesired geomorphic effects.

SUMMARY

The Mad River has undergone significant geomorphic changes since 1992. We quantified these geomorphic changes by using the extensive cross section and air photo data set and explored possible relationships to gravel extraction. The following condenses what we learned from this analysis.

Changes in Stored Sediment

The large, unconfined upstream sites have been major losers of stored sediment, largely through bank erosion rather than downcutting, while the confined or semi-confined downstream sites have undergone significant aggradation.

Between 1993 and 1997 the three upstream bars experienced moderate net channel enlargement, while the two downstream bars underwent slightly greater net filling, leaving the upstream reach as a whole slightly aggraded as of 1997 (aggradation occurred chiefly in 1993-94; see Fig. 28). From 1997 to 2003 the upstream sites, with the exception of Johnson Bar, experienced massive channel enlargement due mainly to channel widening and bank erosion. Our estimate of 960,000 cu.yd. net loss in 1997-2003 compares well with Fehlman's (2004, p. 7) estimate of "more than 800,000 cubic yards." Most of the enlargement occurred in 1998–2000 (Fig. 28), with a decreasing rate of enlargement since 2001. Overall, from 1993-2003, the upstream reach lost about 945,000 cu. yd., or 95,000 cu. yd./year. Our air photo-based analysis of bank erosion volume for 1993-2003 yielded a value of about 1,081,000 cu. yd. (all of which was from the upstream reach), agreeing reasonably well with the volume based on XS alone using the double-end-area method.

With the exception of Essex Bar in 1993-1997, all downstream sites have experienced persistent net aggradation (filling) since 1993. From 1993-2003, the downstream reach gained about 425,000 cu. yd., or 43,000 cu. yd./year. Thus for the mining reach as a whole, there was a net loss of about 520,000 cu. yd for the 11-year period.

Active Channel Area

Active channel areas since 1951 have roughly tracked peak flows (see Fig. 5), with the most significant increases in active channel occurring in response to large floods (e.g., Dec., 1955 and Dec., 1964). Large floods appear to widen the active channel, while extended periods with no large floods allow the channel to narrow as vegetation destroyed by the previous large flood encroaches on fresh deposits. The largest flood of record (81,000 cfs) occurred in December, 1964 (water year 1965), causing widespread destruction of previously stable floodplain and terrace surfaces and resulting in an active channel area of about 1000 acres, or twice that today. The active channel shrunk back to the pre-1964 condition within about a decade, and continued to shrink until the early 1980s, when it became quasi-stable at about 600-700 acres. Although active channel area has increased steadily since 1992, it remains below 700 acres.

Cross Sectional Changes

Temporal and spatial relationships were evaluated between extraction volumes and several measurements taken from the cross sections: mean XS and thalweg elevation, XS area and width, and channel confinement.

For mean XS elevation, a relatively strong ($r^2 = 0.85$) inverse linear relation between 1997-2002 volume extracted and 1997-2003 change in mean elevation at upstream sites was found (see Fig. 32B). No such relation exists for the downstream sites. The decrease of mean elevation with increasing extraction at upstream sites is what one would logically expect, and suggests that the inverse relation between mean elevation and extraction is not merely an artifact of the amount of extraction permitted, but may have predictive value. The pattern for mean thalweg elevation changes is similar to that described above for mean elevation, since thalweg elevation tends to track mean XS elevation.

For the 1993-96 period, no consistent relation between mean width change and volume extracted at either upstream or downstream sites (see Fig. 36A). However, for the 1997-2002 period, mean width change strongly parallels volume extracted at relatively unconfined upstream sites, i.e., greater extraction volumes are accompanied by greater increases in width (see Fig. 36B). In the confined downstream reach the relation is weak because cross-section width stays nearly constant, regardless of volume extracted. Relationships between extraction volume and changes in width were similar to those for XS area. Little quantitative relation between channel confinement changes and amount of gravel extracted.

We found inverse linear relations between volume extracted and change in mean XS area at both upstream and downstream sites for the 1993-1996 period (see Fig. 39A). The upstream relation for 1993-1996 was moderate ($r^2 = 0.71$), while for later period (1997-2002), a strong ($r^2 = 0.95$) positive linear relation between change in mean XS area at upstream sites and volume extracted was found (see Fig. 39B). Mean XS area change appears independent of volume extracted at downstream sites.

Strong positive relations between volume change and volume extracted (Figs. 42A-B) are what one would expect if a causal relation exists. Following additional aggradation in 1997-98, sediment input from upstream has been relatively modest (see Fig. 44) and mining and the river have been removing material from storage (Fig. 27). As with cross-section area, this would lead to channel volume increasing in step with volume of gravel extracted. The lack of relation in the downstream reach reflects its persistent aggradation.

Implications for gravel extraction

The upstream reach of the Lower Mad River functions differently from the downstream reach in ways that determine its response to gravel extraction. Since the late 1990's the upstream reach has lost about one million cu. yd. of stored bed and bank material. During the same period, the downstream reach has aggraded. Our '*zero effect*' analysis suggests that an annual mean extraction rate of about 55,000 – 85,000 cu. yd./year from the upstream reach should have minimal effect on channel enlargement under current conditions. Actual extraction from this reach has averaged 135,000 cu. yd./year.

We reiterate that we are not recommending that upstream extraction be reduced to this "zero-effect" amount due to inherent uncertainty (scatter) in regression analysis. However, we are confident in saying that the upstream reach cannot support extraction in excess of the current amount (135,000 cu. yd./year) without undesired effects (continued large losses in stored sediment and attendant habitat impacts), and that it would be prudent to manage the upstream reach for smaller annual average volumes.

As stated earlier, the downstream reach has undergone persistent deposition since 1993. Although mean annual extraction has been 44,000 cu. yd./year, mean yearly net deposition (stored sediment volume increase) has amounted to 42,000 yd^3/year for the same period. This suggests that it might be possible to increase extraction in the downstream reach without undesirable consequences. An increase in extraction equal to half the mean net deposition (i.e., 15,000-20,000 cu. yd./year) does not seem unreasonable if it is balanced by reductions in extractions from the upstream reach. It would still allow annual mean net aggradation of 15,000 – 20,000 yd^3/year, which would presumably limit undesired geomorphic effects.

Conclusion: This analysis suggests that, *under current conditions*, overall "zero effect" extraction on the Mad River is on the order of 85,000 yd^3/year for the upstream reach and 50,000 – 70,000 yd^3/year for the downstream reach, or a total of 135,000 – 155,000 yd^3/year for the entire river. Given the uncertainties in this approach, the current average extraction of 175,000 yd^3/year is not unreasonable, but certainly appears to be an upper limit. The 270,000 yd^3/year that Kondolf and Lutrick (2001) suggest might be extracted appears much too high, while the 112,000 yd^3/year suggested by Knuuti and McComas (2003) is probably unnecessarily low.

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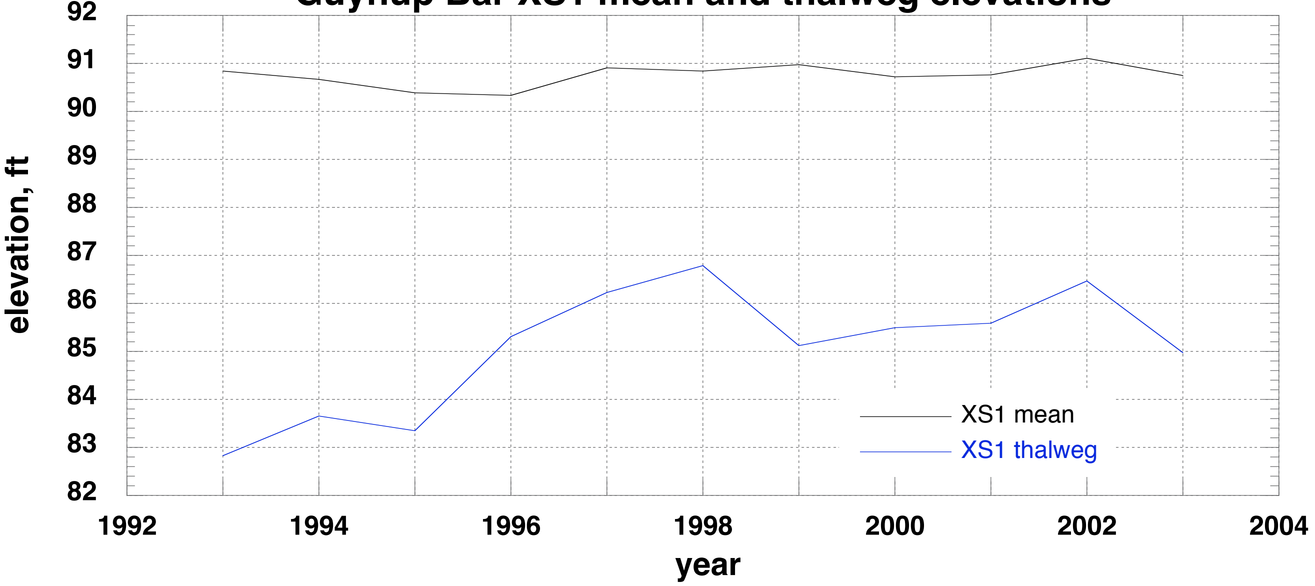
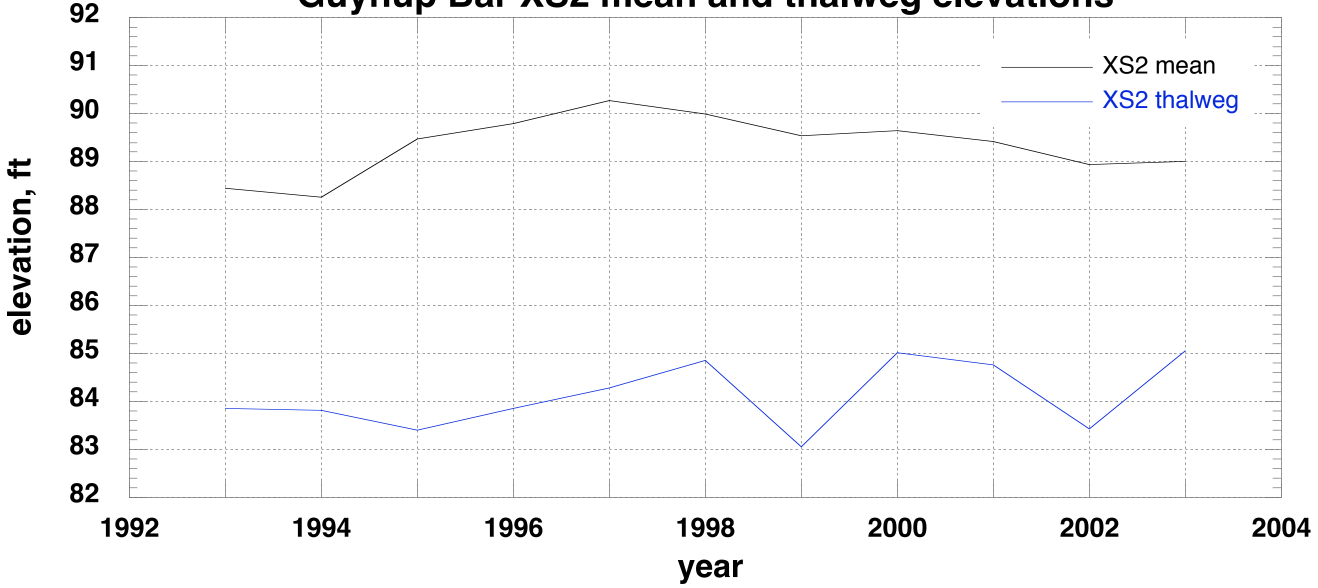
Appendix A

XS mean & thalweg elevation vs time for each XS

Guynup Bar XS1 mean and thalweg elevations



Guynup Bar XS2 mean and thalweg elevations



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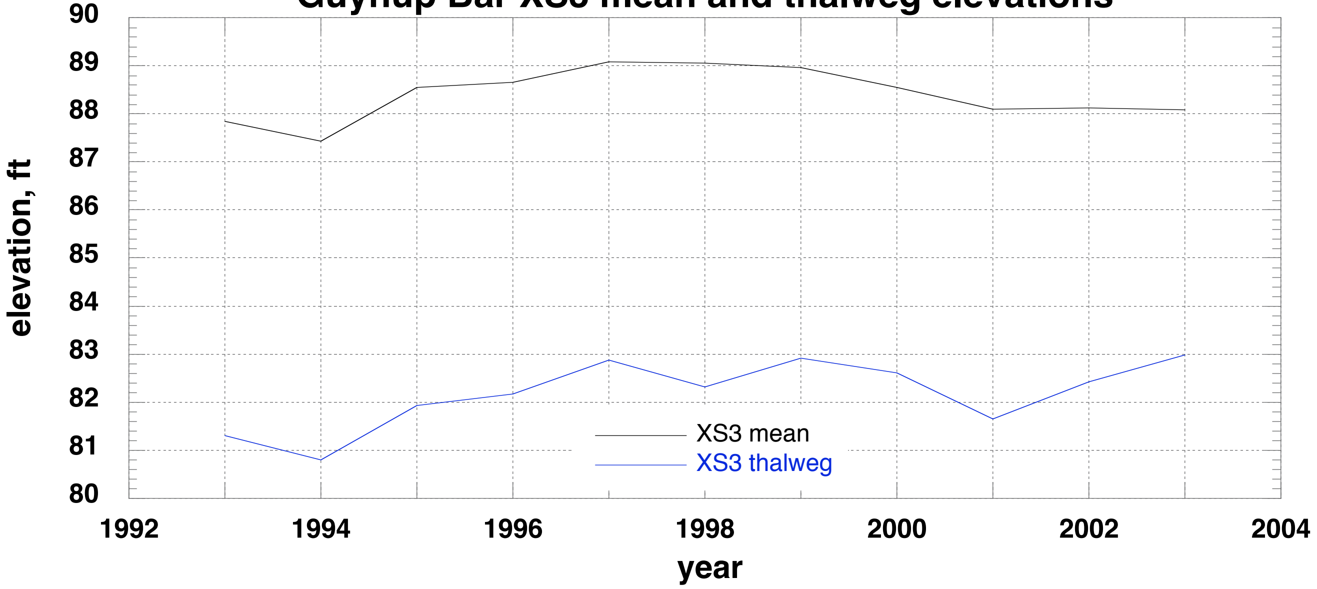

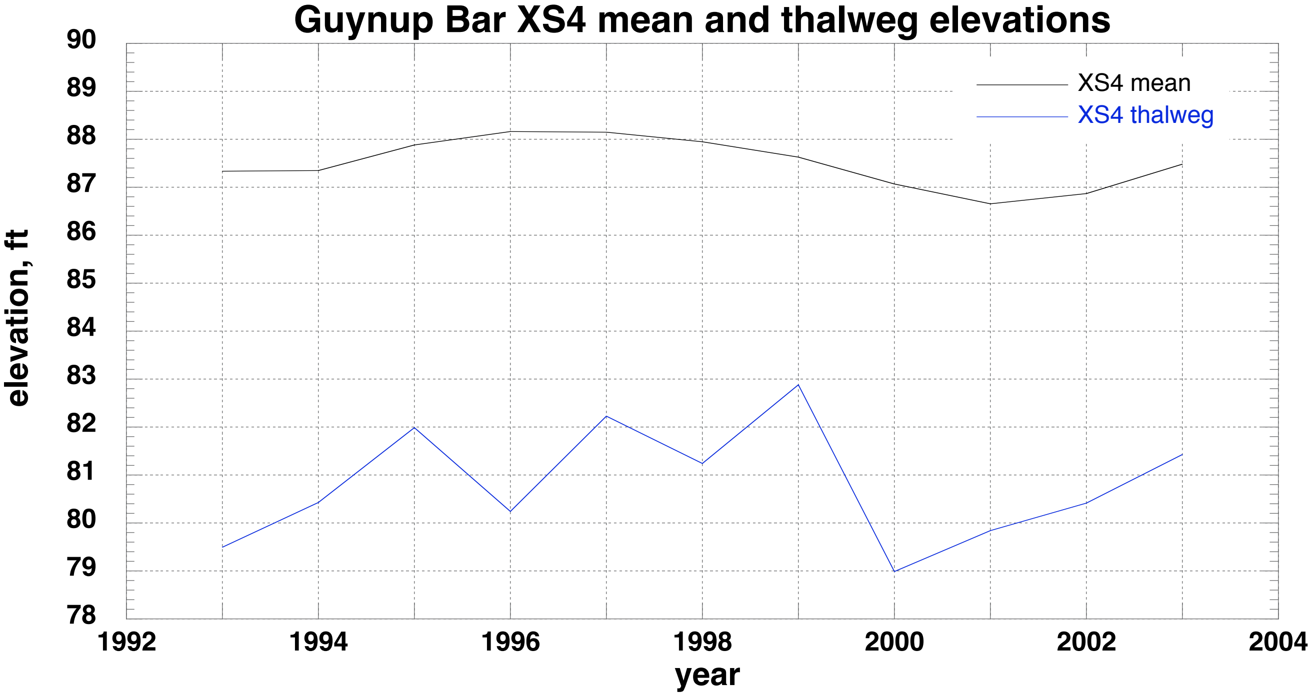
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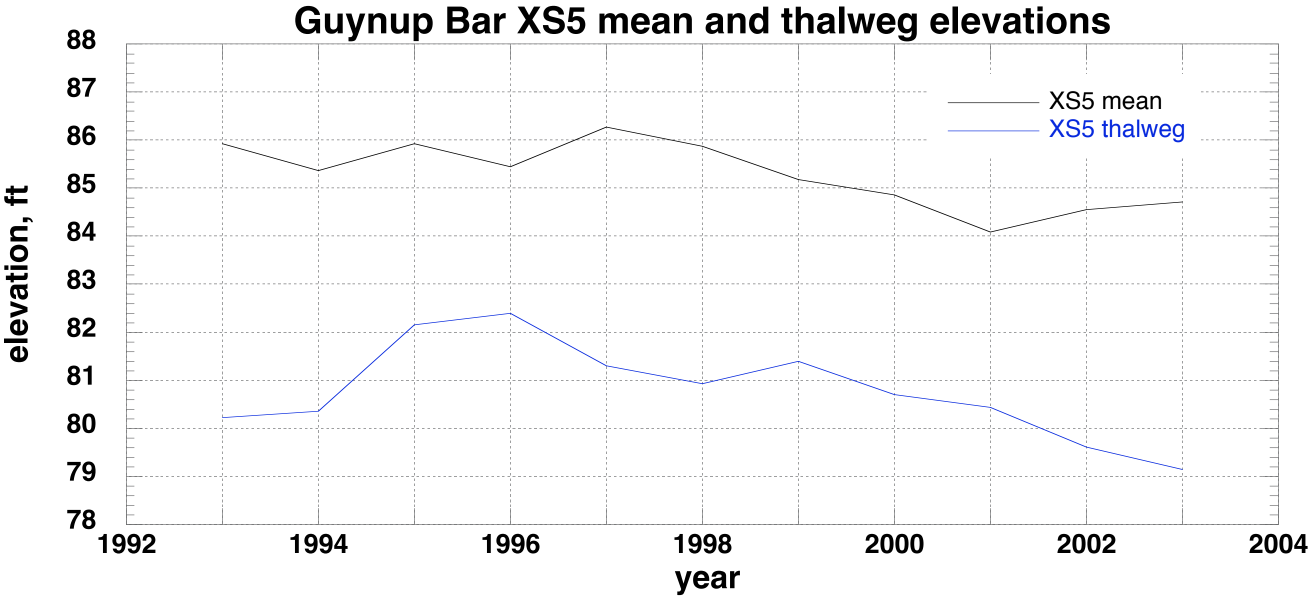
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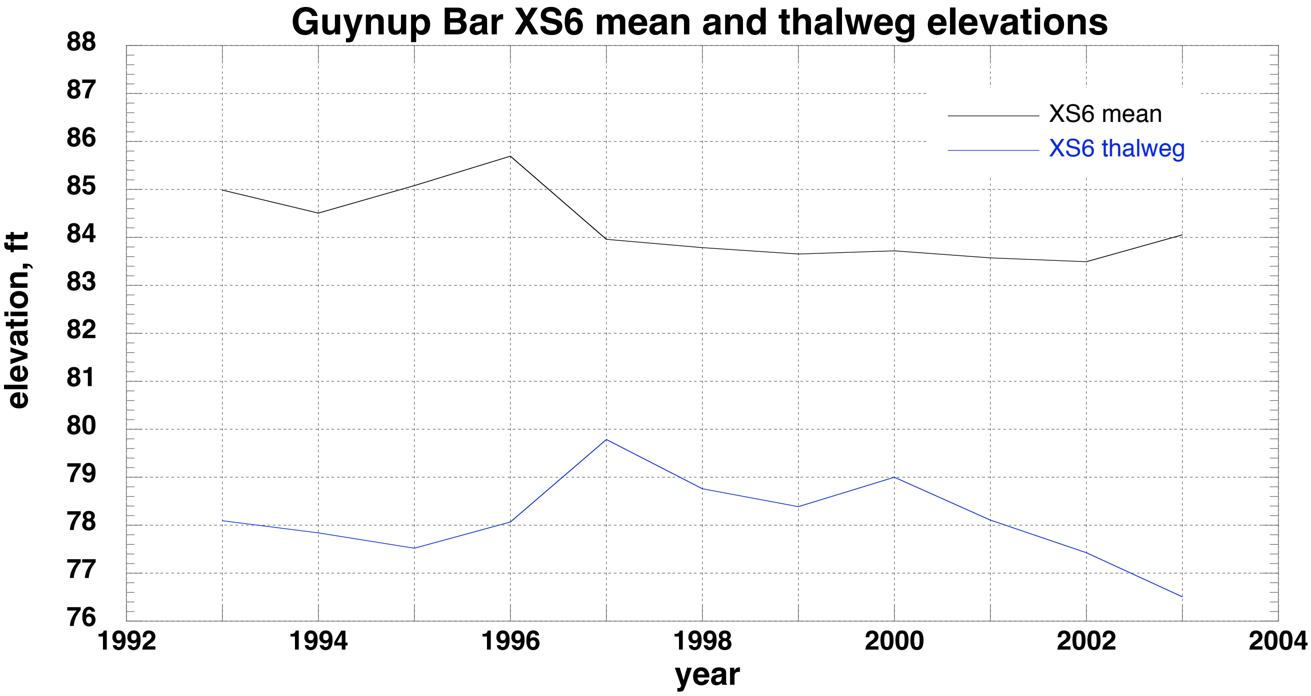
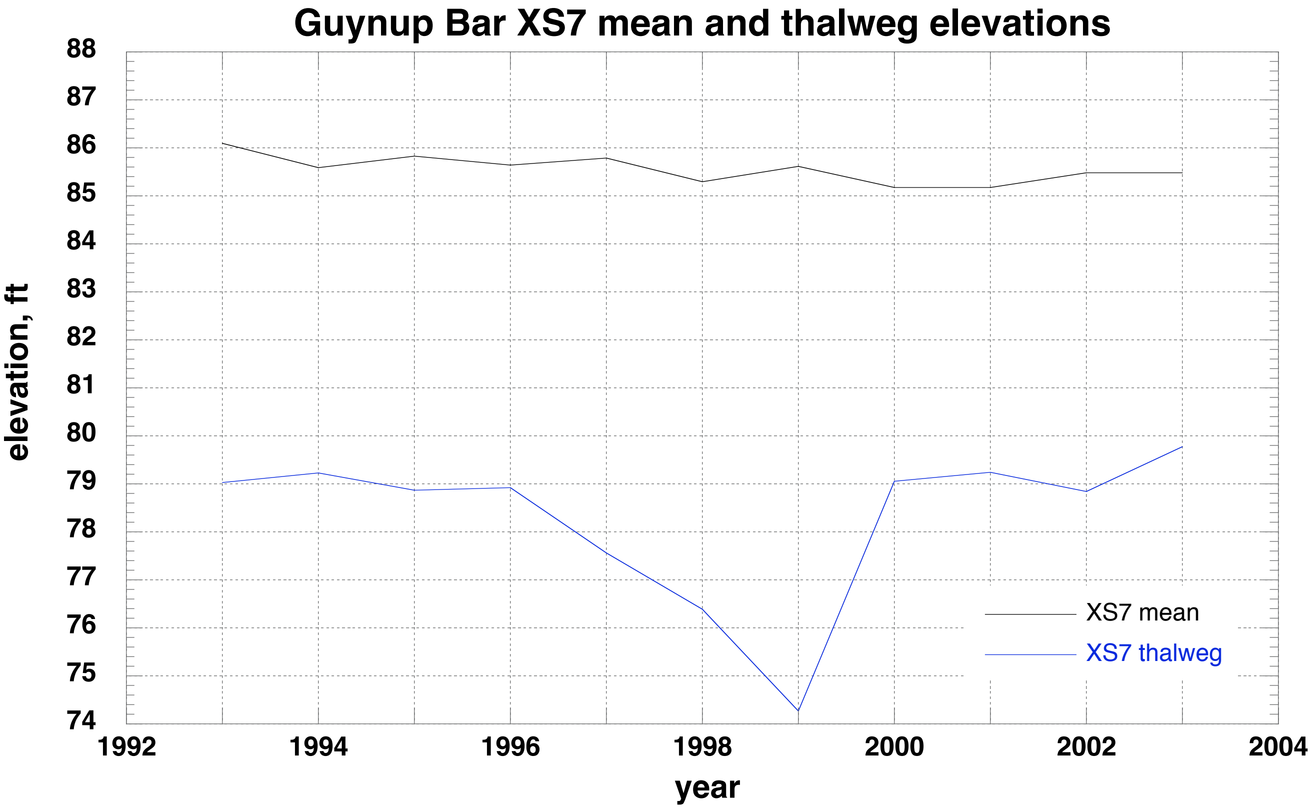
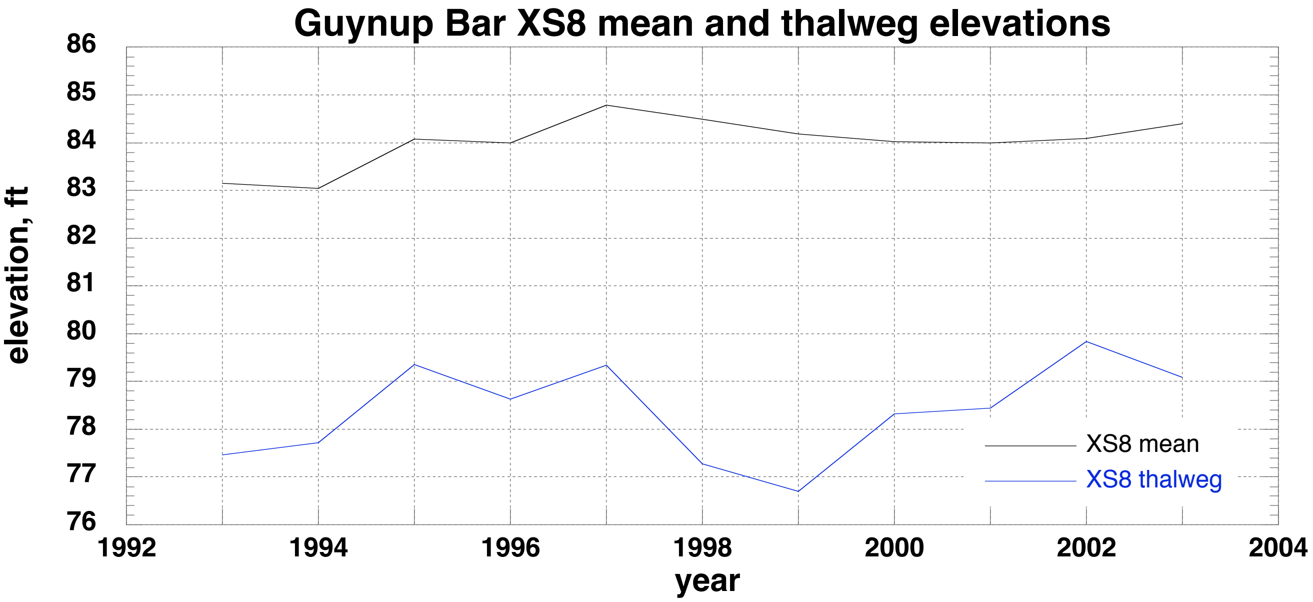
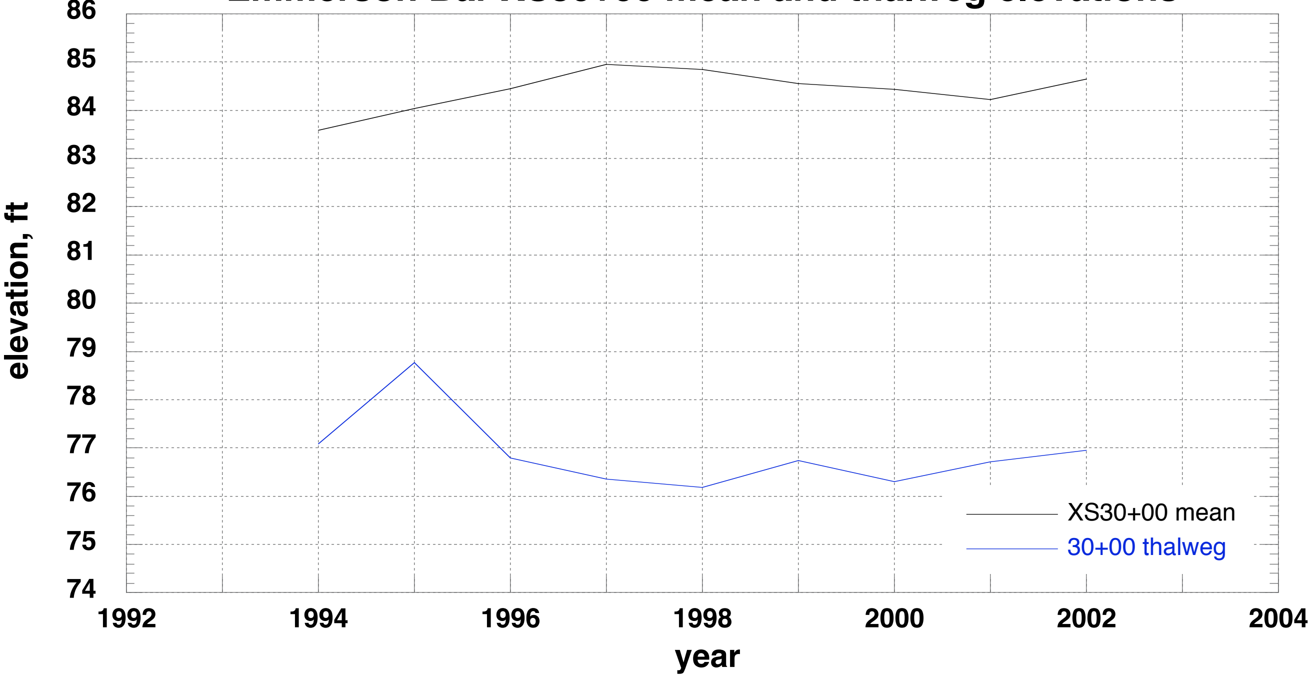
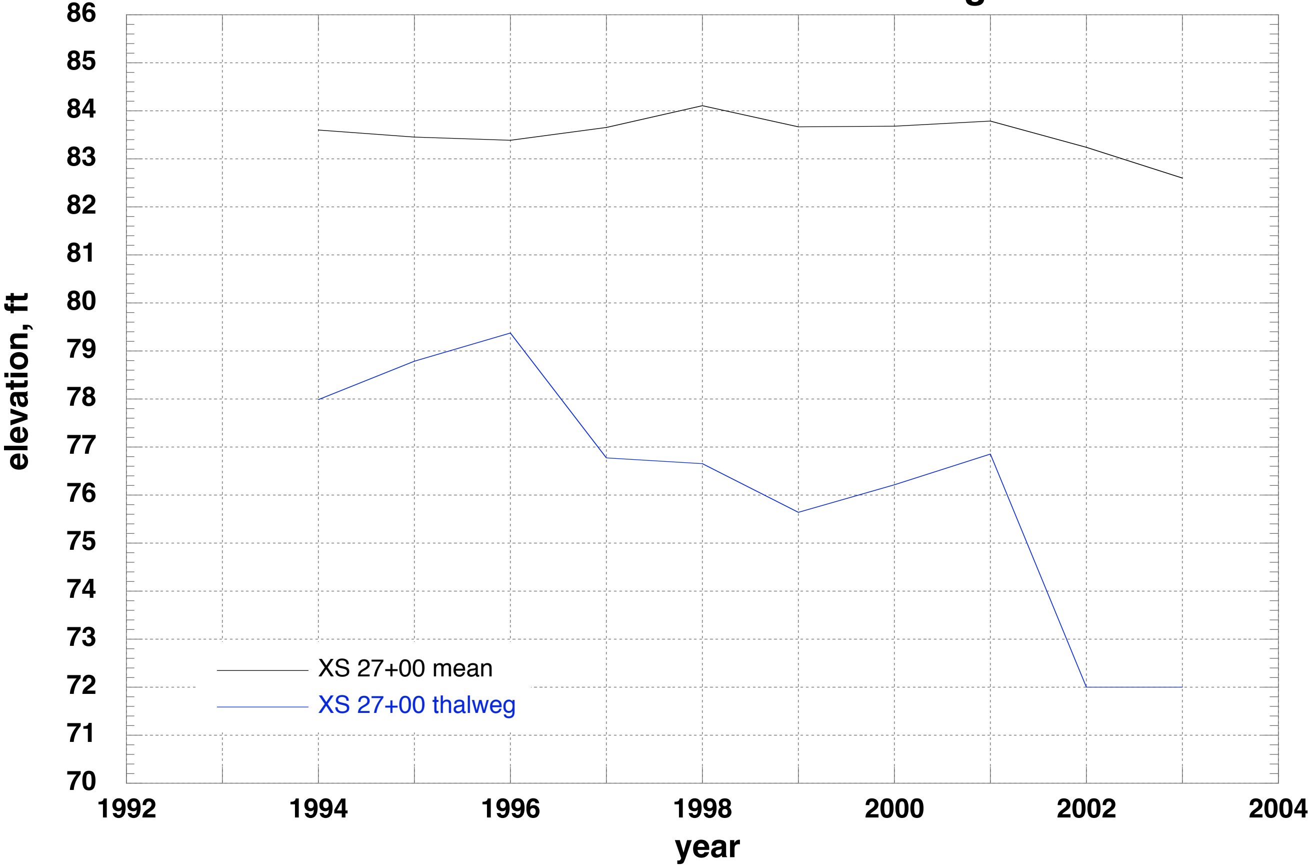

Guynup Bar XS6 mean and thalweg elevations


Guynup Bar XS7 mean and thalweg elevations
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
elevation, ft
1992
1994
1996
1998
2000
2002
2004
year
XS7 mean
XS7 thalweg


Guynup Bar XS8 mean and thalweg elevations
86
85
84
83
82
81
80
79
78
77
76
elevation, ft
1992
1994
1996
1998
2000
2002
2004
year
XS8 mean
XS8 thalweg


Emmerson Bar XS30+00 mean and thalweg elevations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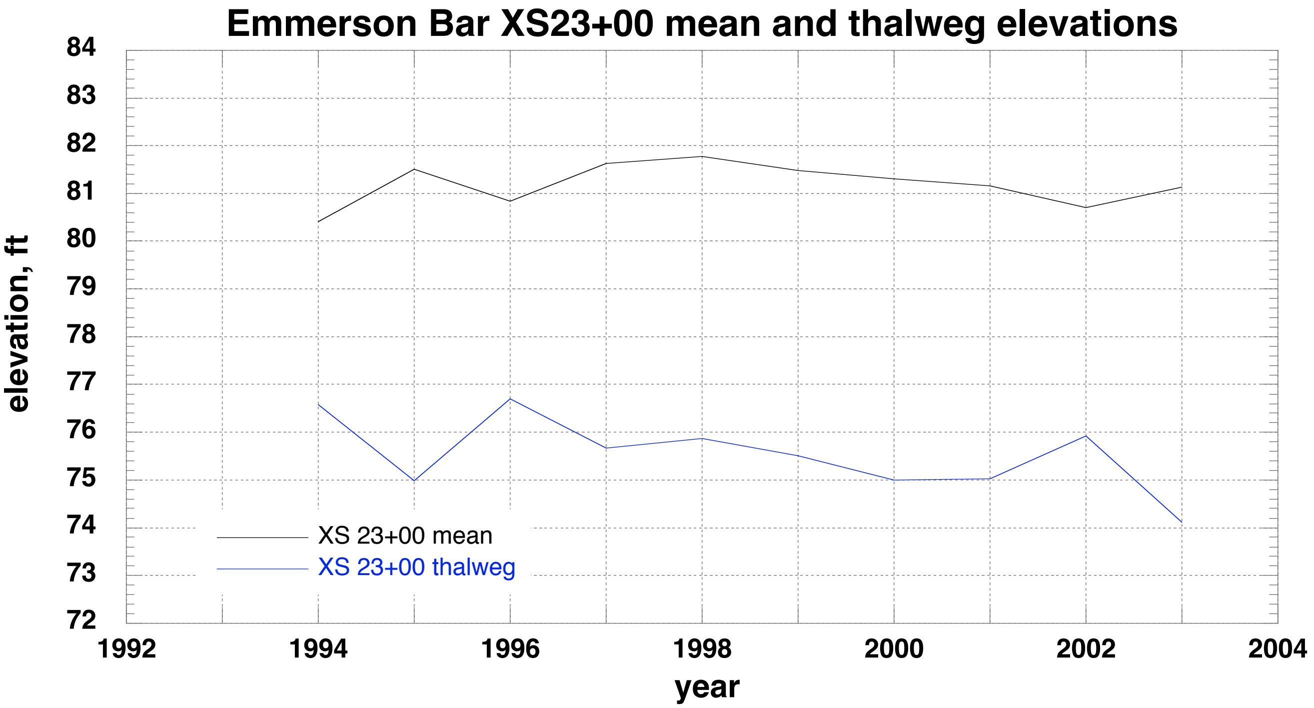
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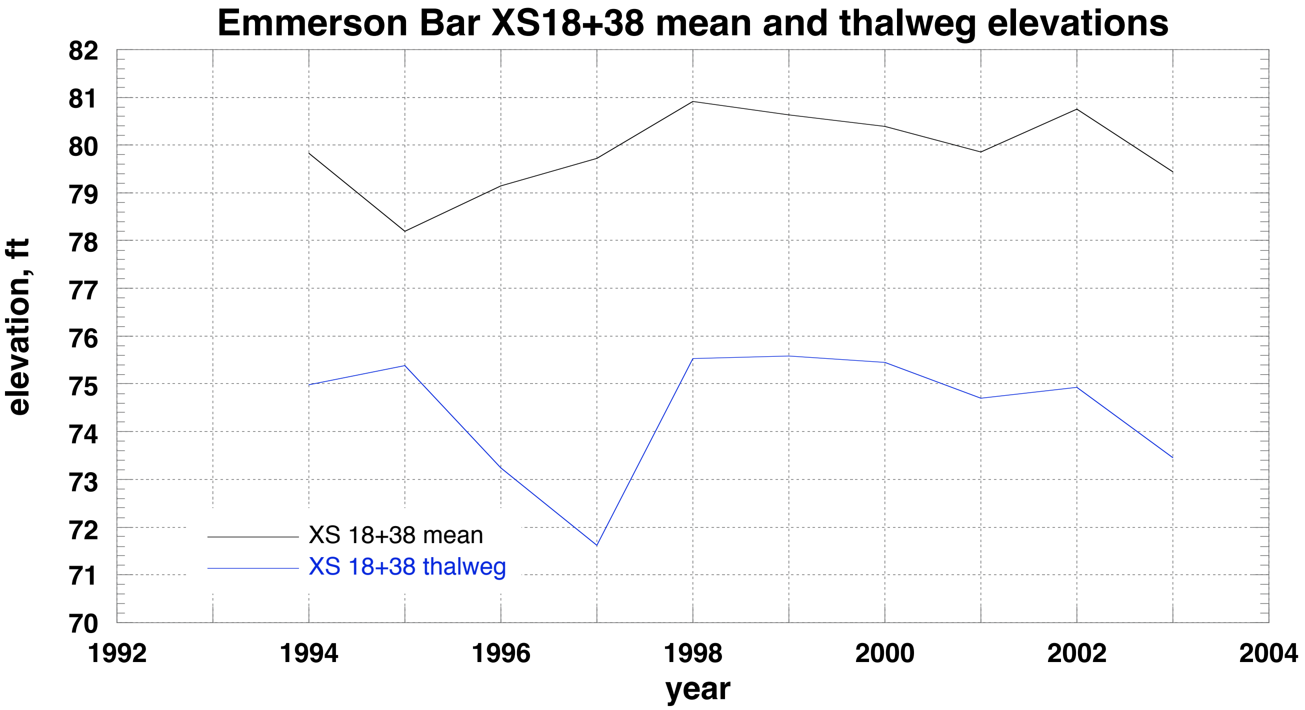
elevation, ft
84
83
82
81
80
79
78
77
76
75
74
73
72
1992
1994
1996
1998
2000
2002
2004
year
XS 23+00 mean
XS 23+00 thalweg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elevation, ft
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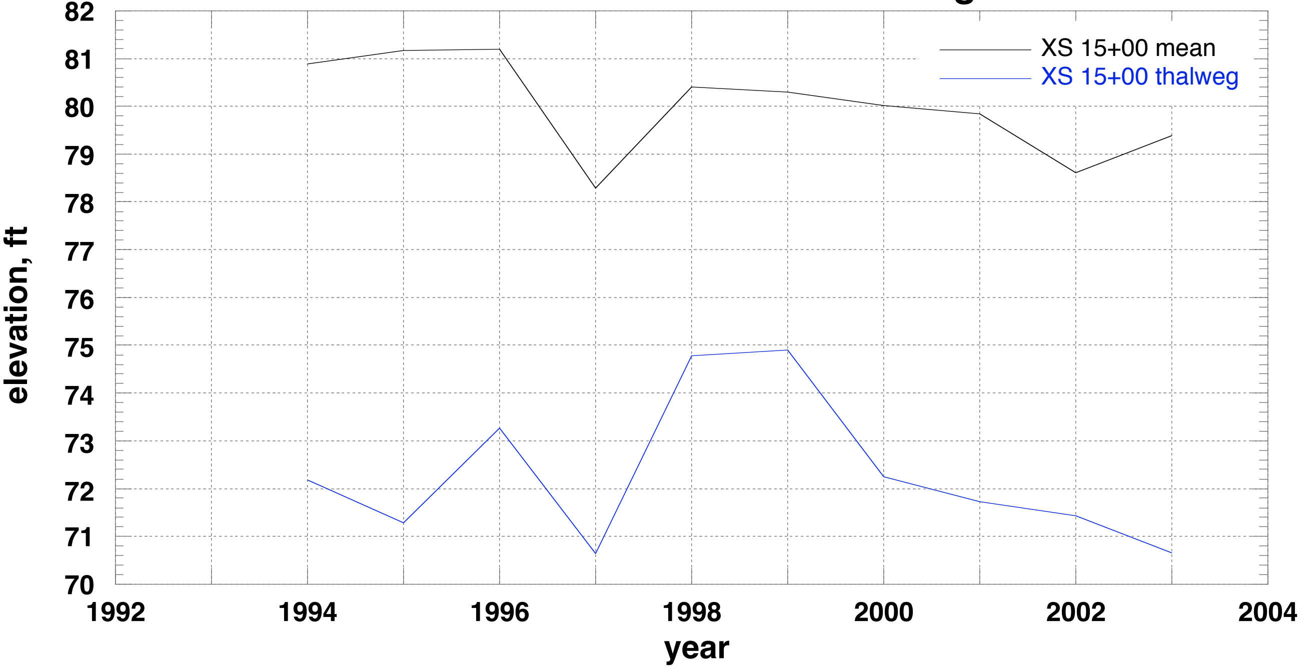
81
80
79
78
77
76
75
74
73
72
71
70
1992
1994
1996
1998
2000
2002
2004
year
XS 18+38 mean
XS 18+38 thalweg



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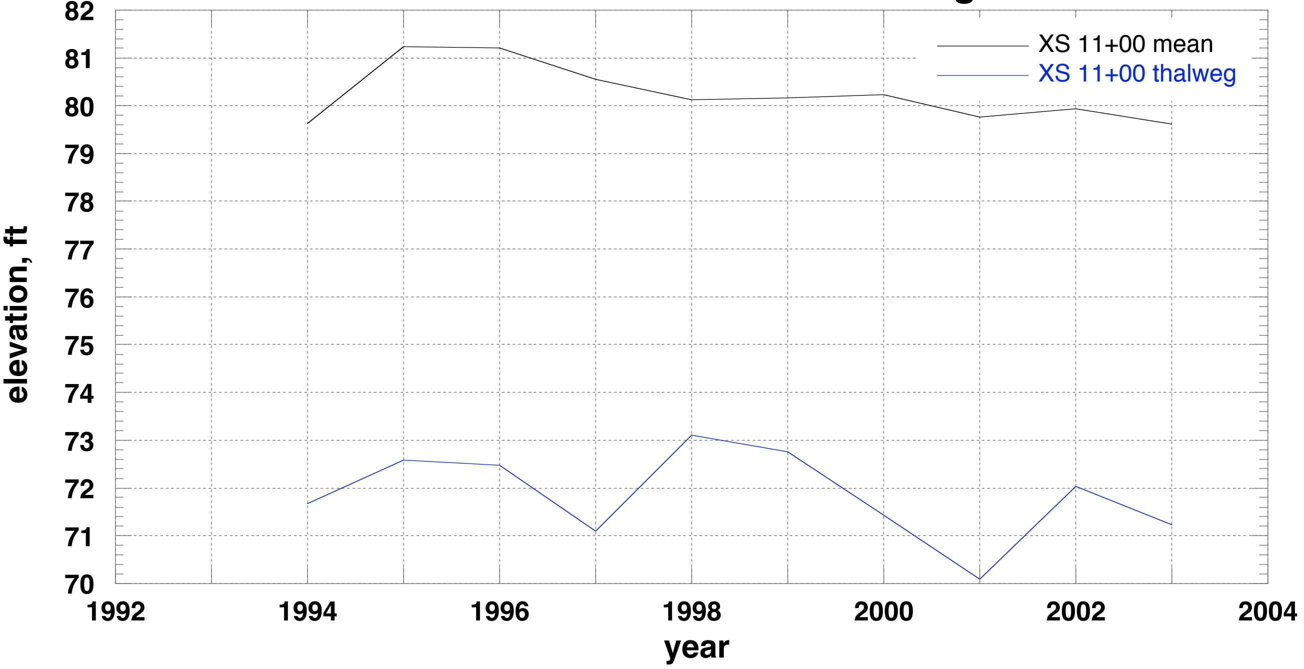

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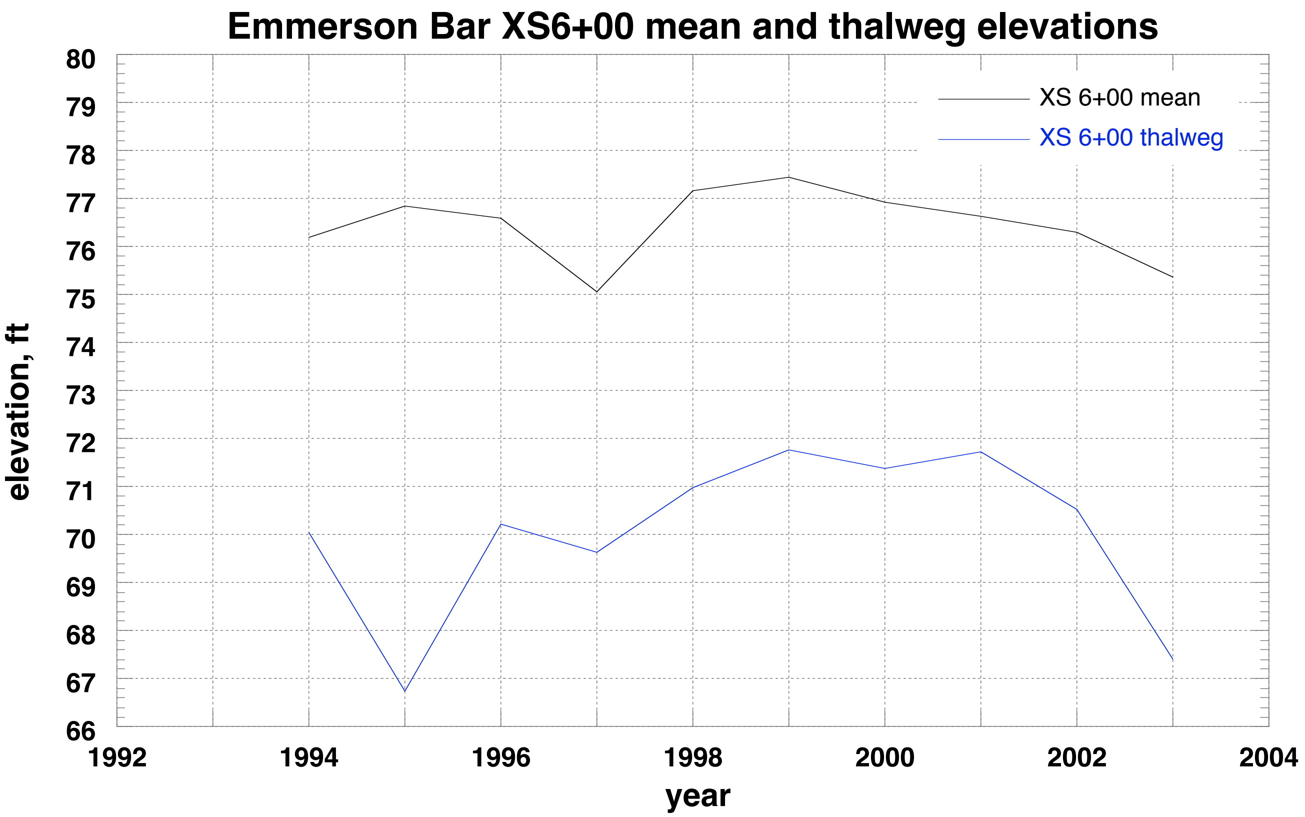
Emmerson Bar XS6+00 mean and thalweg elevations
XS 6+00 mean
XS 6+00 thalweg
elevation, ft
80
79
78
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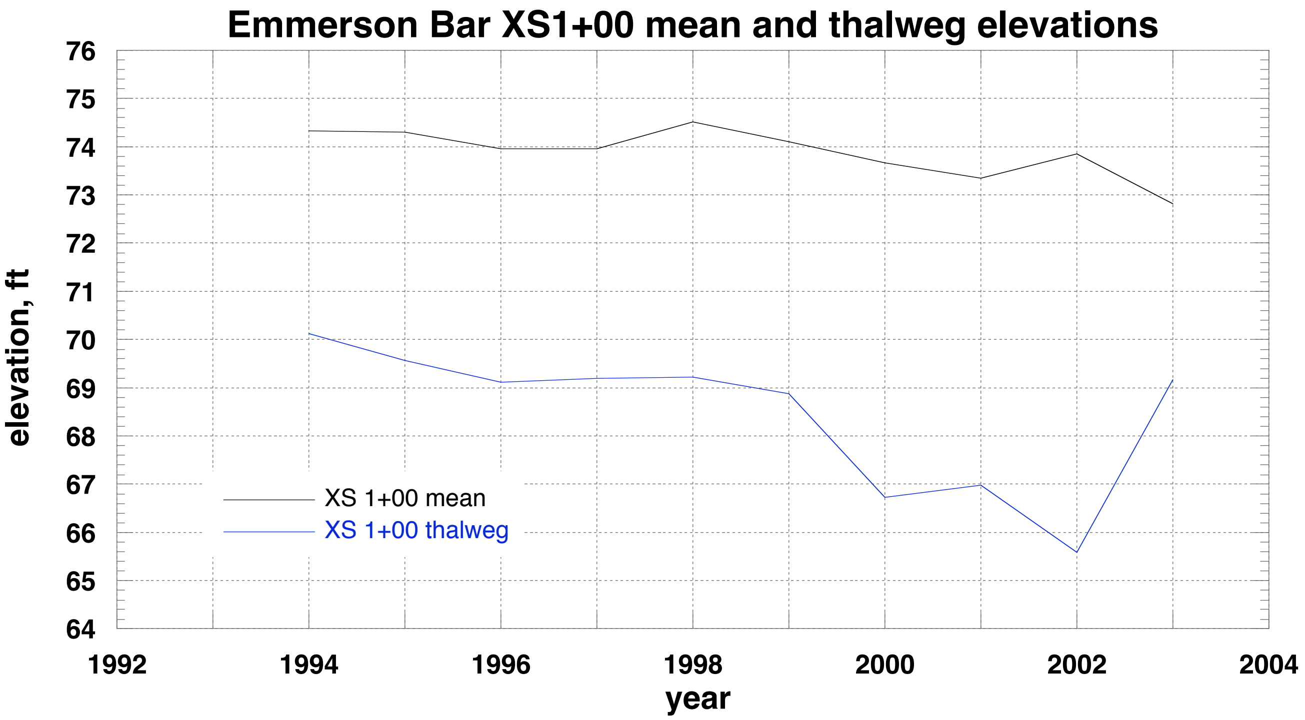
76
75
74
73
72
71
70
69
68
67
66
1992
1994
1996
1998
2000
2002
2004
year


Emmerson Bar XS1+00 mean and thalweg elevations
XS 1+00 mean
XS 1+00 thalweg
elevation, ft
76
75
74
73
72
71
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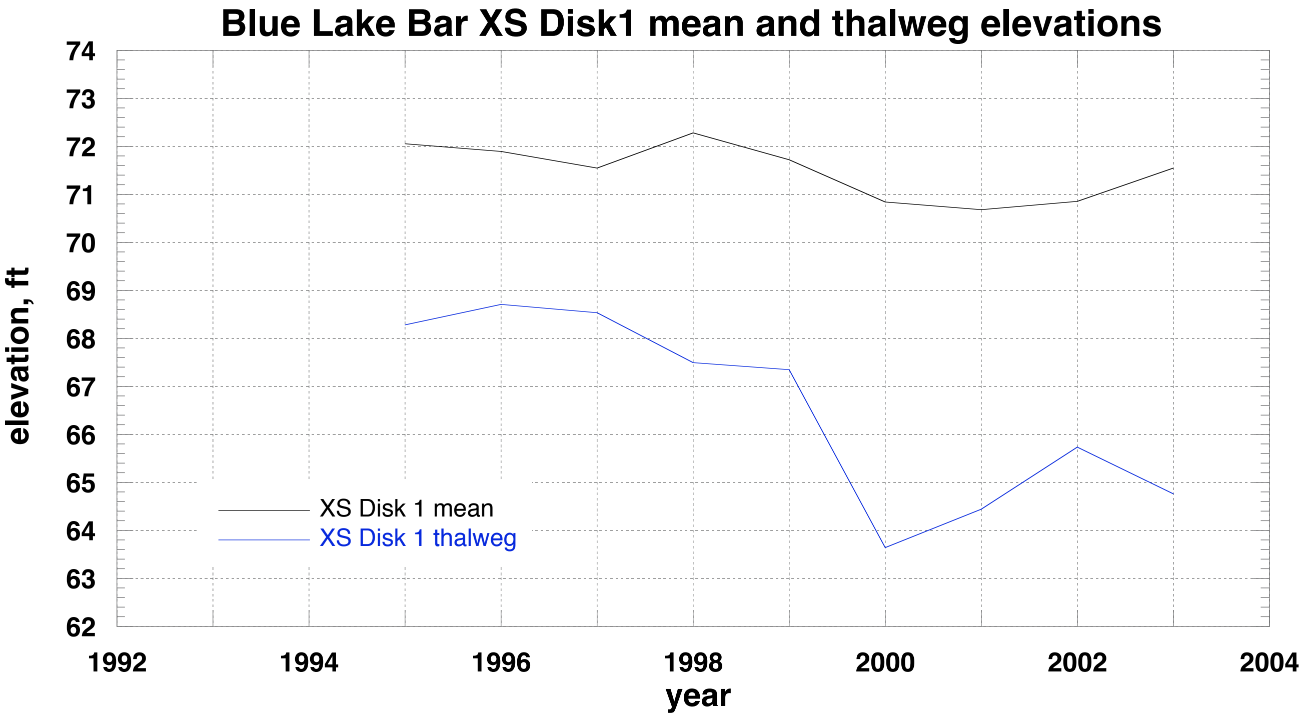
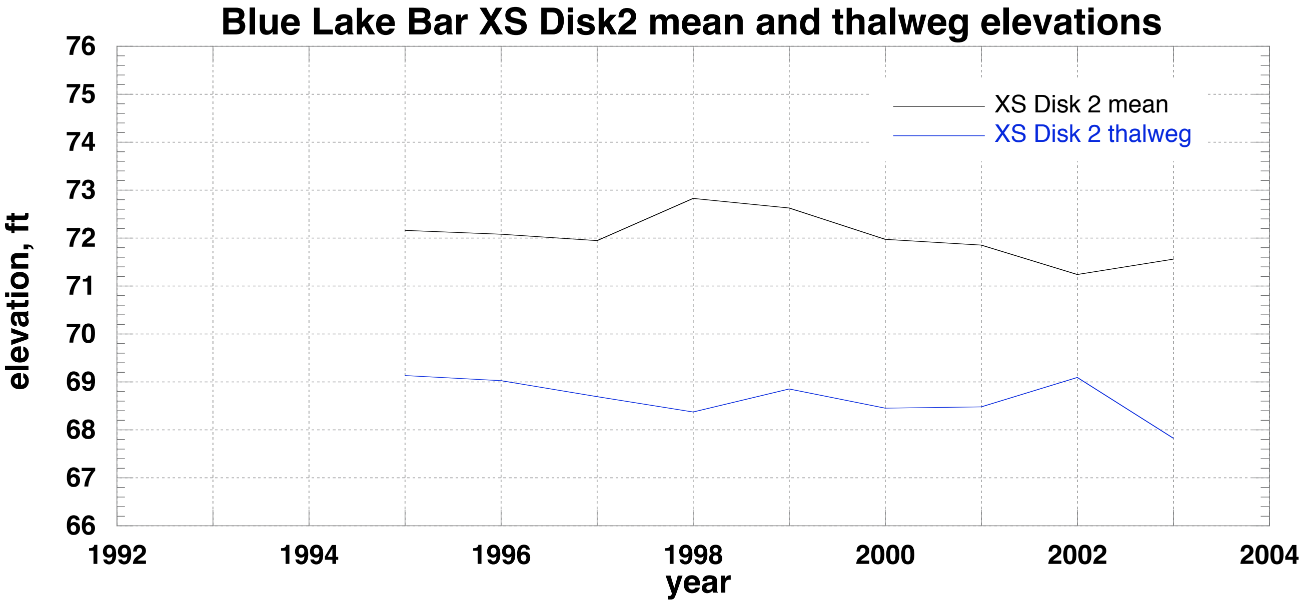
69
68
67
66
65
64
1992
1994
1996
1998
2000
2002
2004
year


Blue Lake Bar XS Disk1 mean and thalweg elevations
elevation, ft
74
73
72
71
70
69
68
67
66
65
64
63
62
1992
1994
1996
1998
2000
2002
2004
year
XS Disk 1 mean
XS Disk 1 thalweg


Blue Lake Bar XS Disk2 mean and thalweg elevations
elevation, ft
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75
74
73
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71
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69
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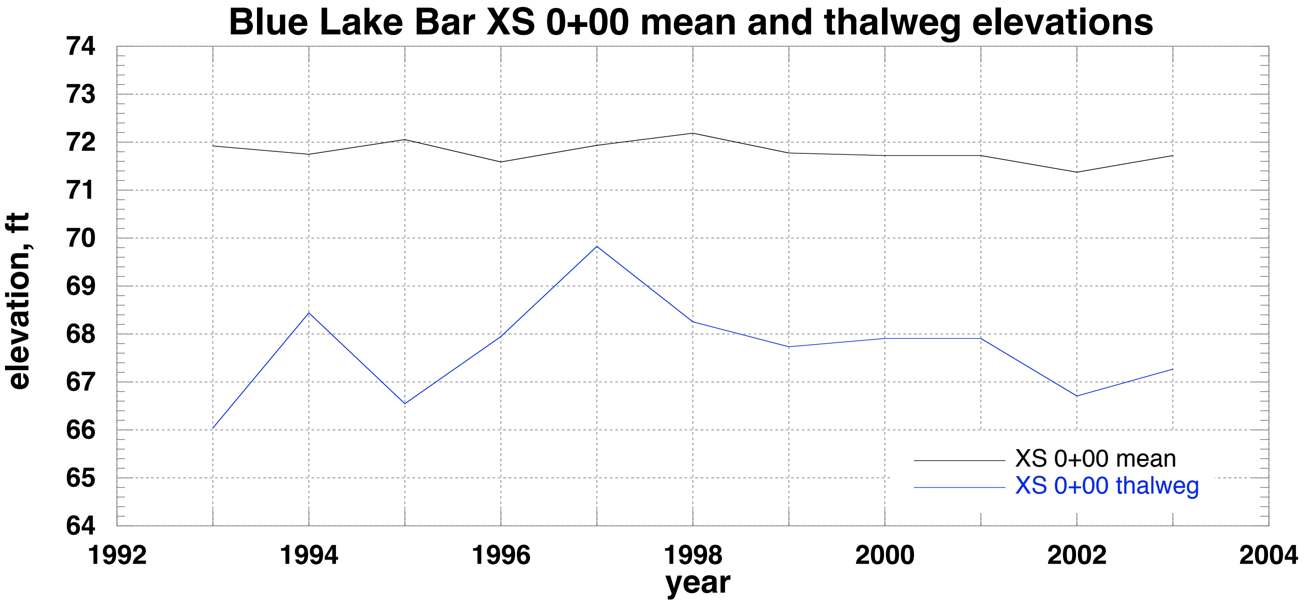
67
66
1992
1994
1996
1998
2000
2002
2004
year
XS Disk 2 mean
XS Disk 2 thalweg


Blue Lake Bar XS 0+00 mean and thalweg elevations
elevation, ft
74
73
72
71
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67
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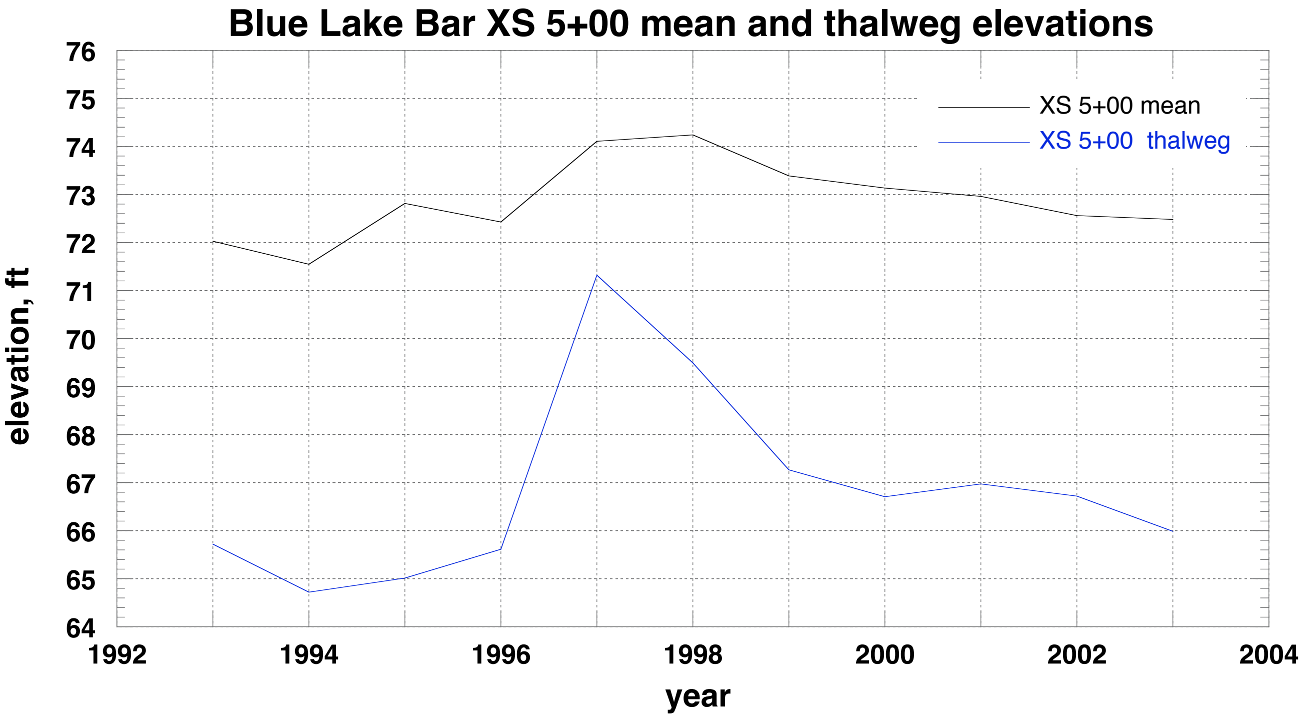
64
1992
1994
1996
1998
2000
2002
2004
year
XS 0+00 mean
XS 0+00 thalweg


Blue Lake Bar XS 5+00 mean and thalweg elevations
elevation, ft
76
75
74
73
72
71
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67
66
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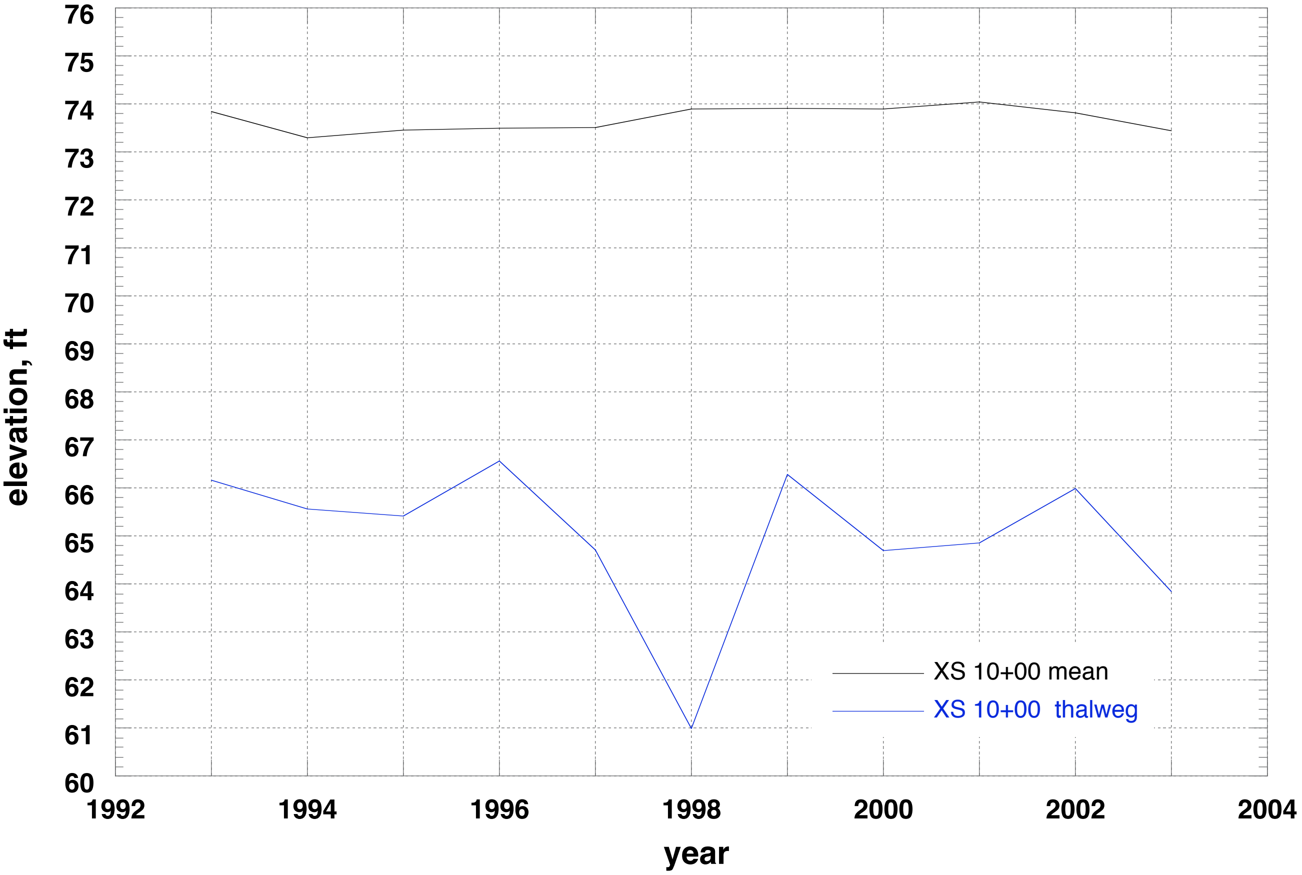
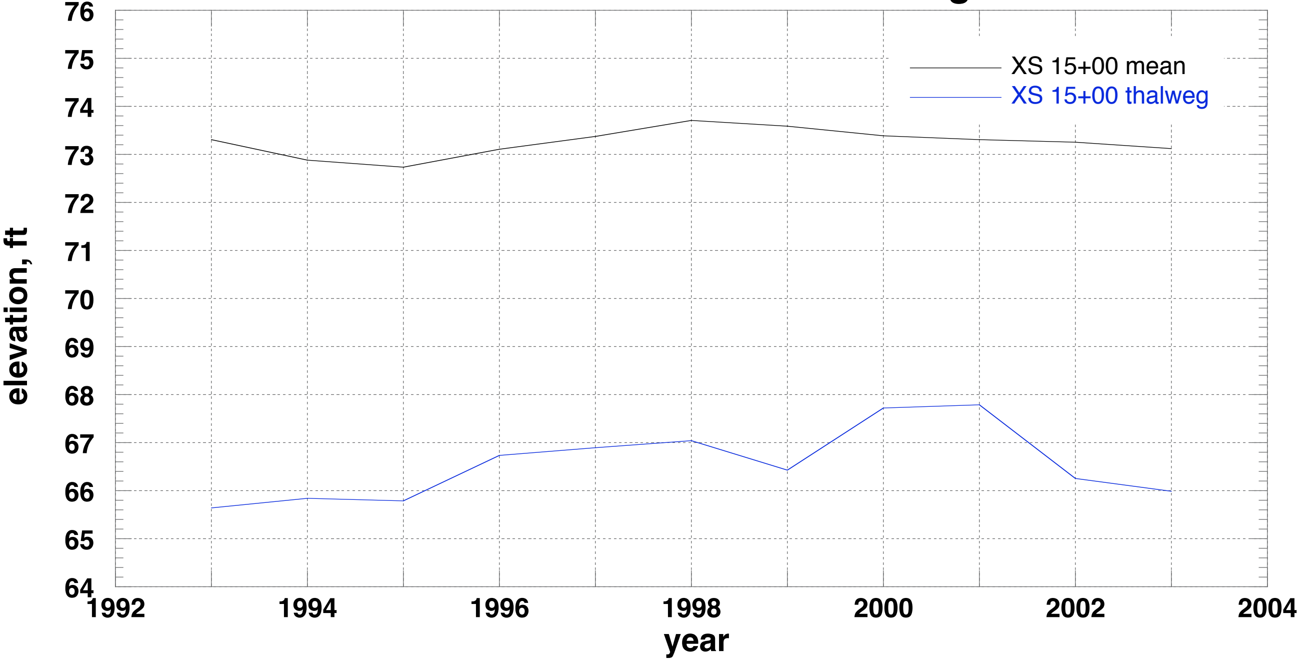
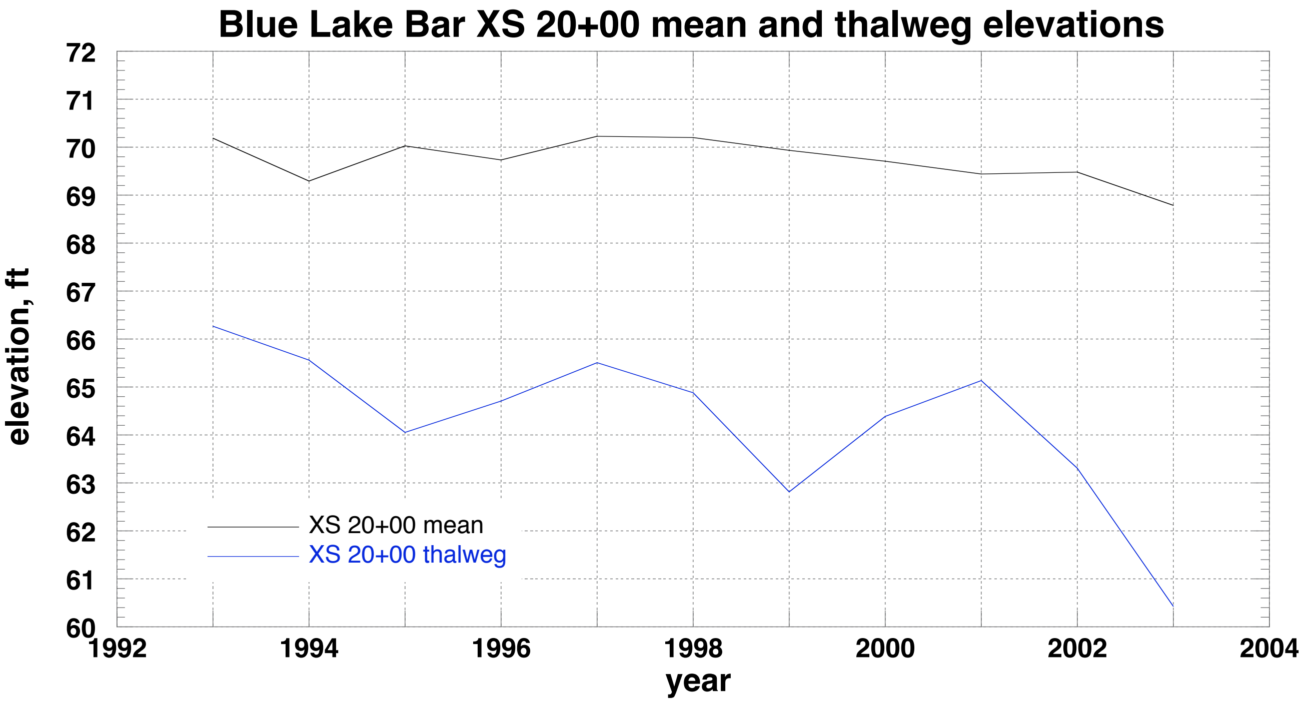
64
1992
1994
1996
1998
2000
2002
2004
year
XS 5+00 mean
XS 5+00 thalweg


Blue Lake Bar XS 10+00 mean and thalweg elevations


Blue Lake Bar XS 15+00 mean and thalweg elevations


Blue Lake Bar XS 20+00 mean and thalweg elevations
elevation, ft
72
71
70
69
68
67
66
65
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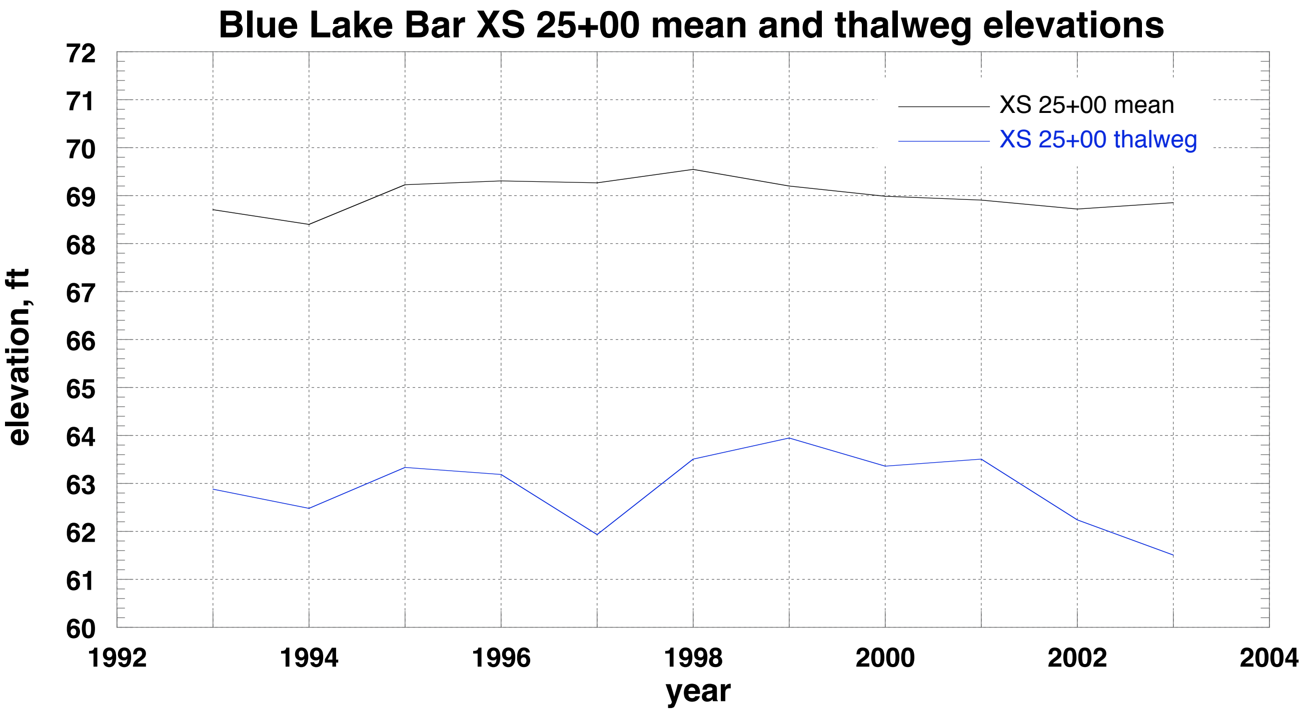
62
61
60
1992
1994
1996
1998
2000
2002
2004
year
XS 20+00 mean
XS 20+00 thalweg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elevation, ft
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71
70
69
68
67
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65
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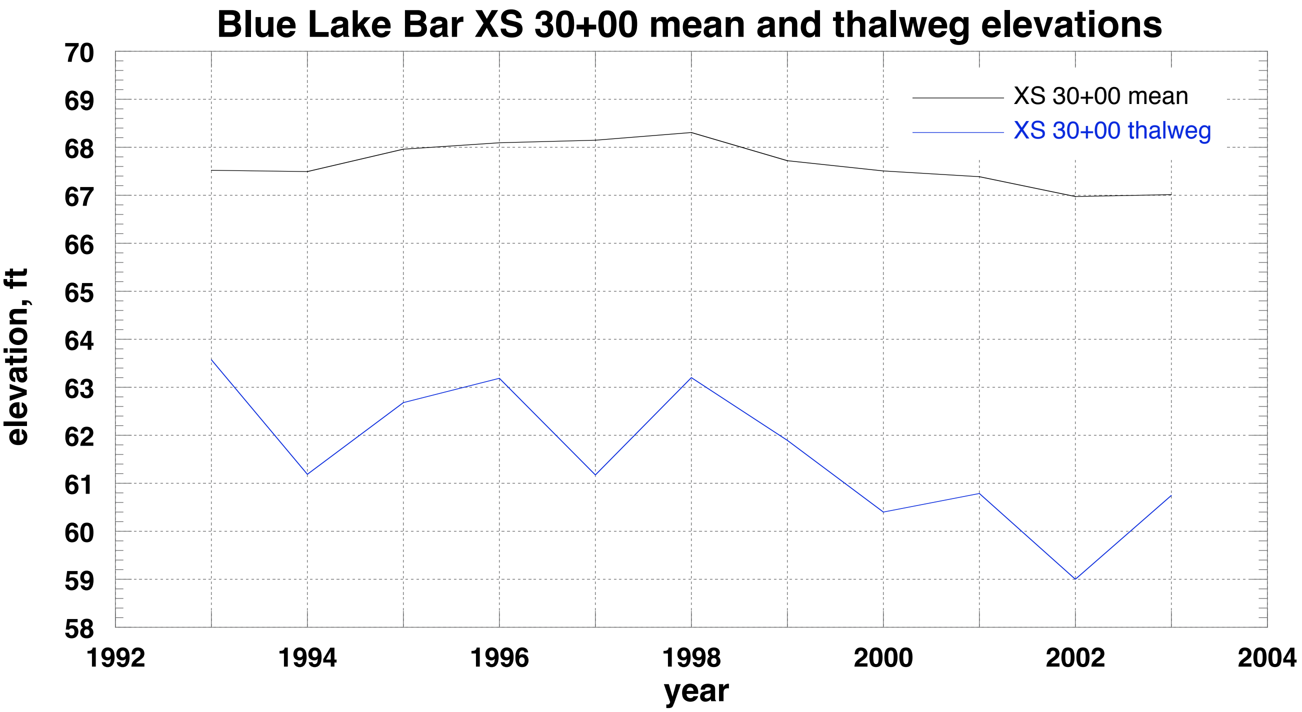
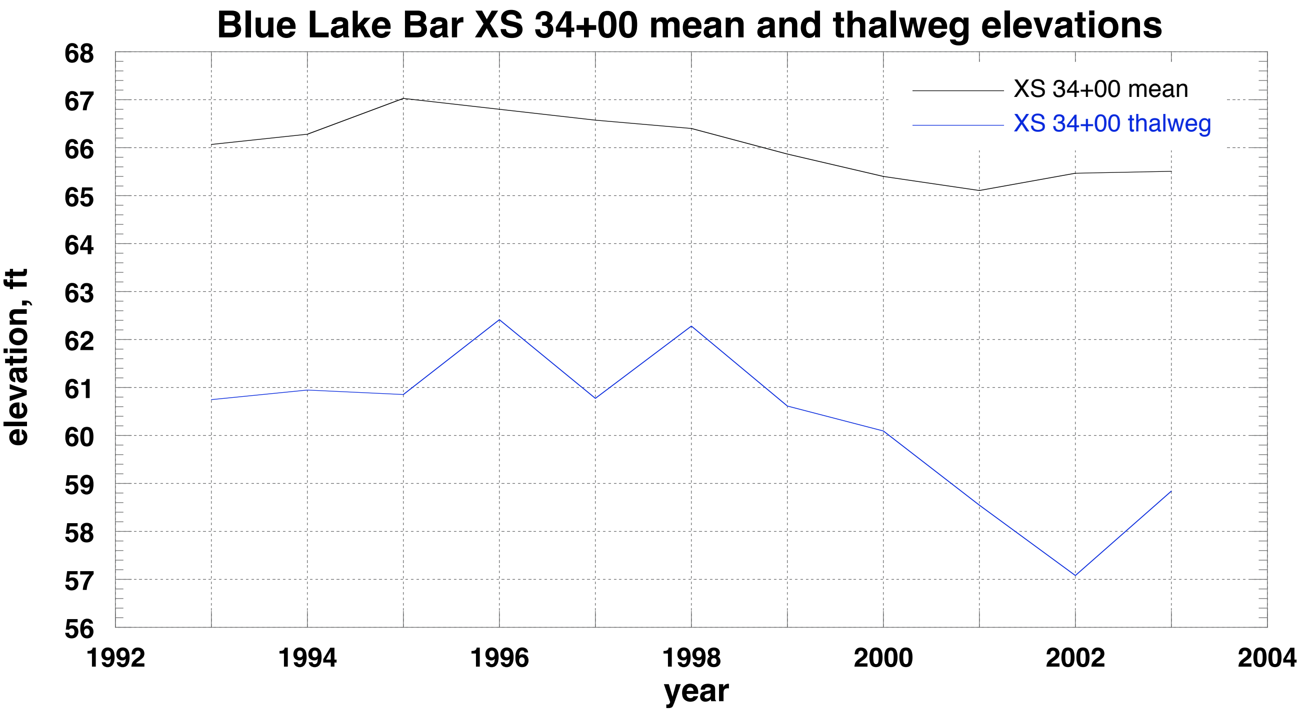
61
60
1992
1994
1996
1998
2000
2002
2004
year
XS 25+00 mean
XS 25+00 thalweg


Blue Lake Bar XS 30+00 mean and thalweg elevations
XS 30+00 mean
XS 30+00 thalweg
elevation, ft
70
69
68
67
66
65
64
63
62
61
60
59
58
1992
1994
1996
1998
2000
2002
2004
year


Blue Lake Bar XS 34+00 mean and thalweg elevations
XS 34+00 mean
XS 34+00 thalweg
elevation, ft
68
67
66
65
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63
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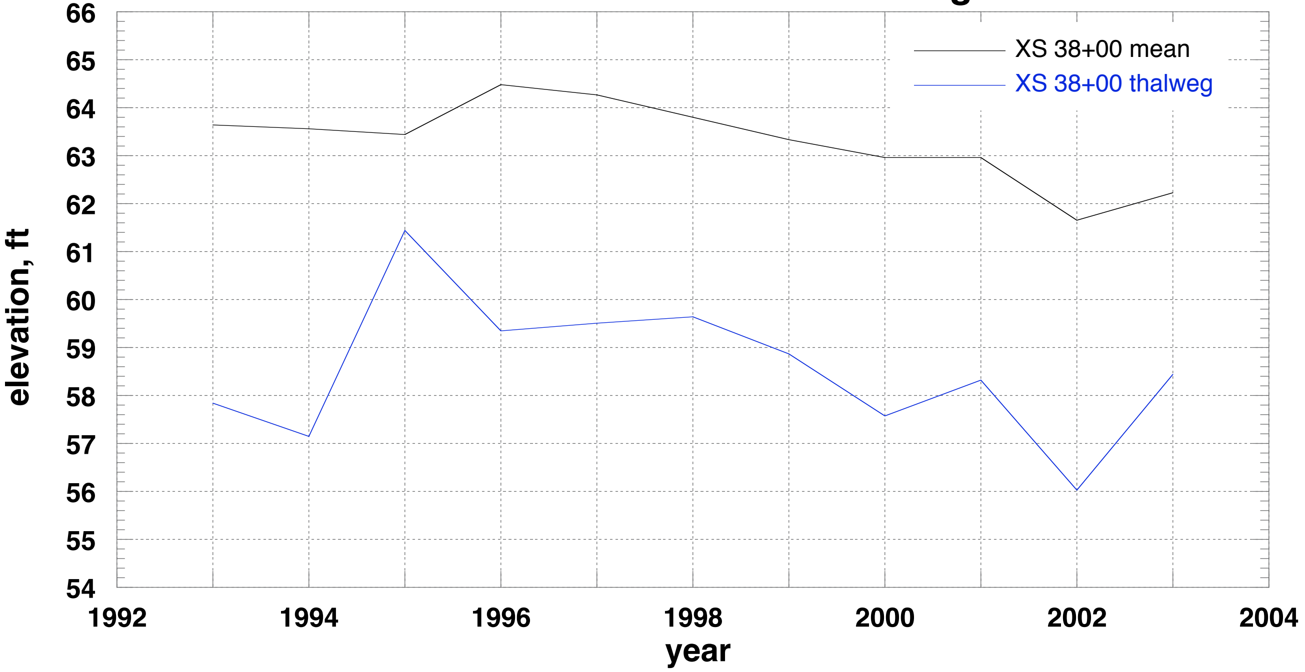
59
58
57
56
1992
1994
1996
1998
2000
2002
2004
year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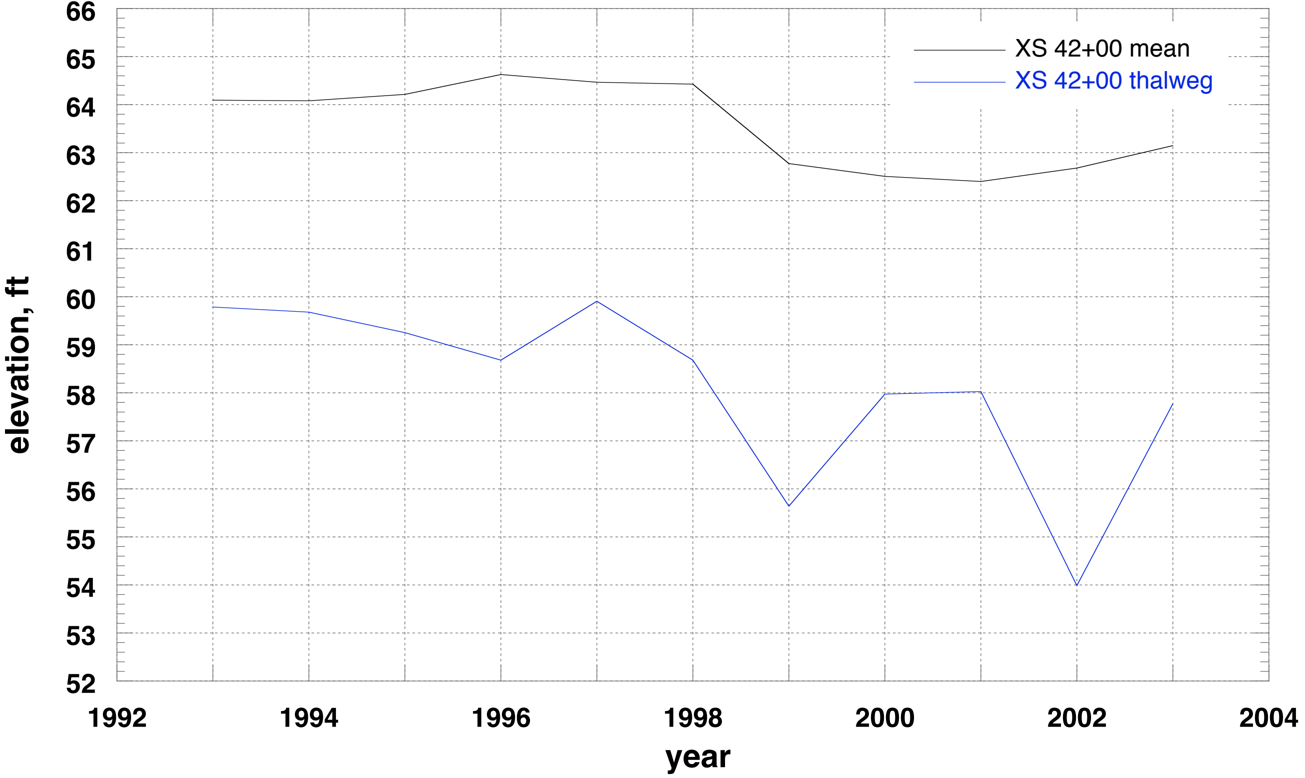
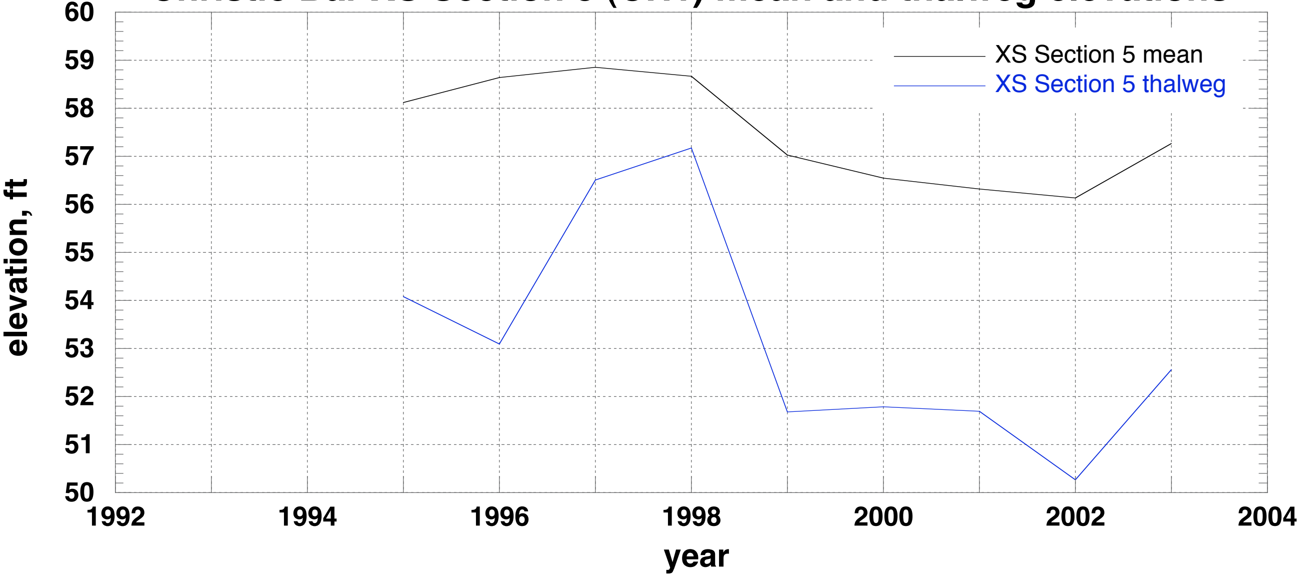
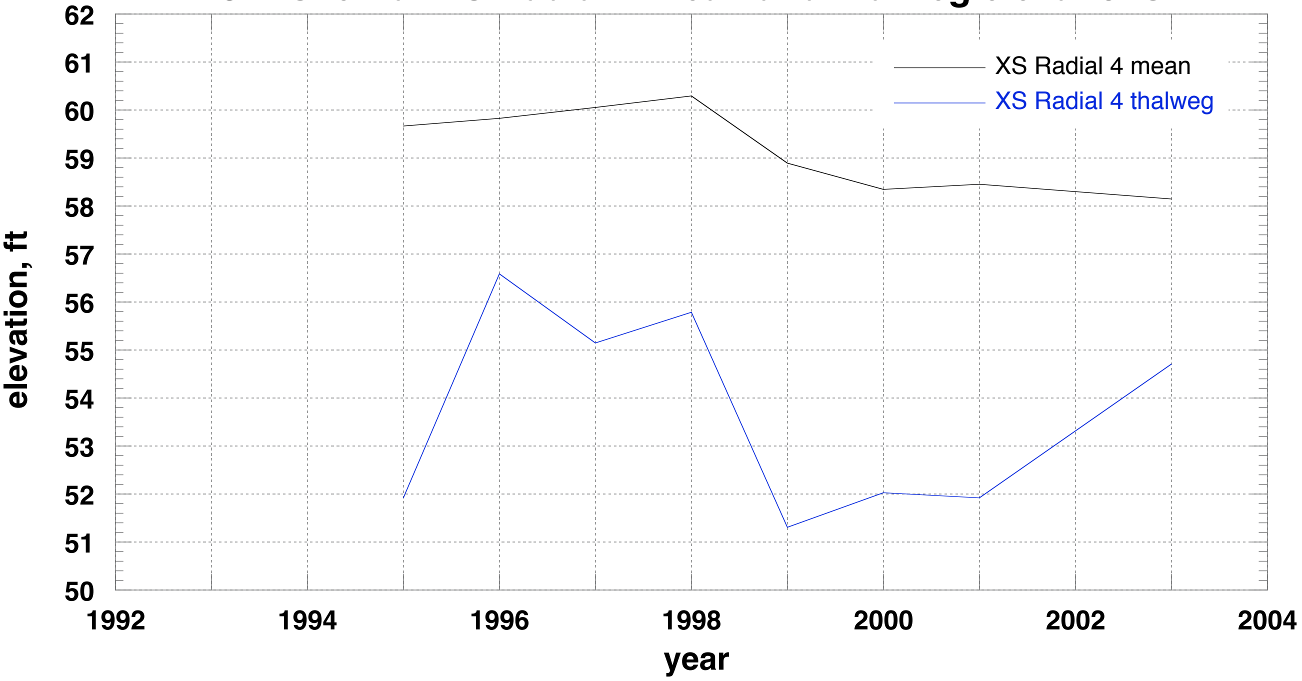
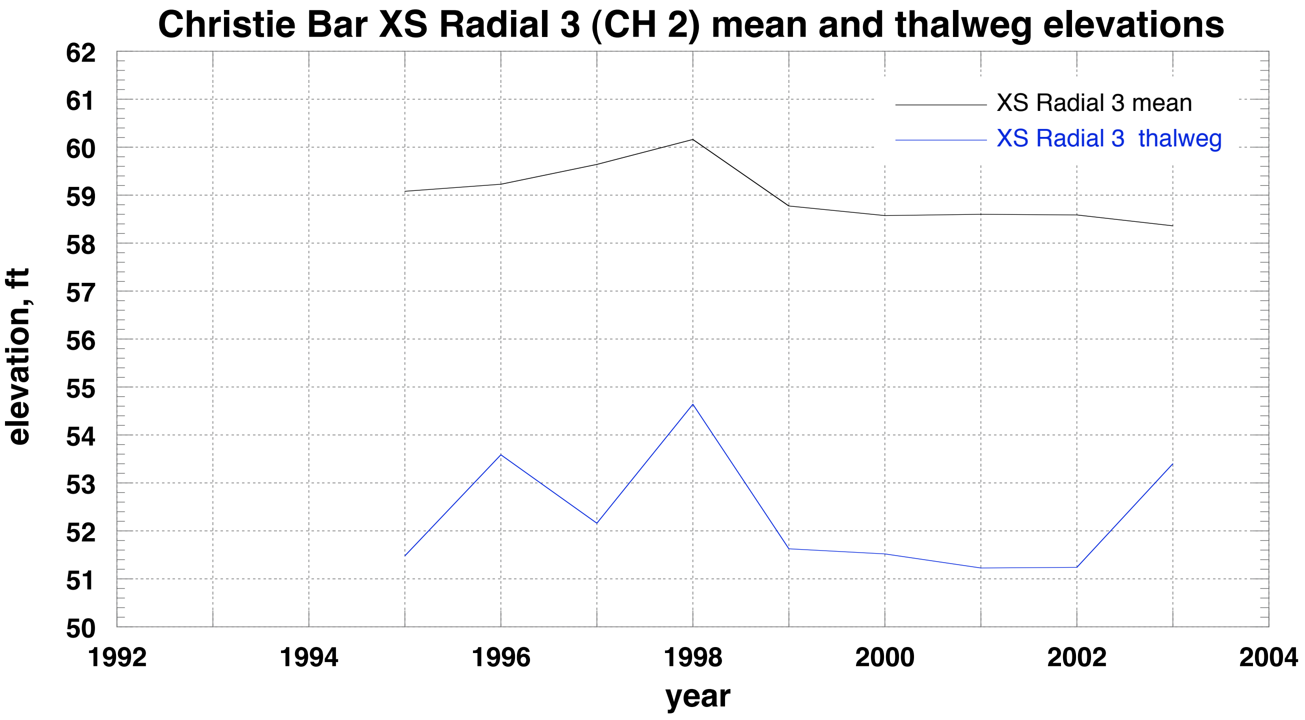

Blue Lake Bar XS 42+00 mean and thalweg elevations

Christie Bar XS Section 5 (CH1) mean and thalweg elevations



Christie Bar XS Radial 4 mean and thalweg elevations




Christie Bar XS Radial 3 (CH 2) mean and thalweg elevations
XS Radial 3 mean
XS Radial 3 thalweg
elevation, ft
62
61
60
59
58
57
56
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54
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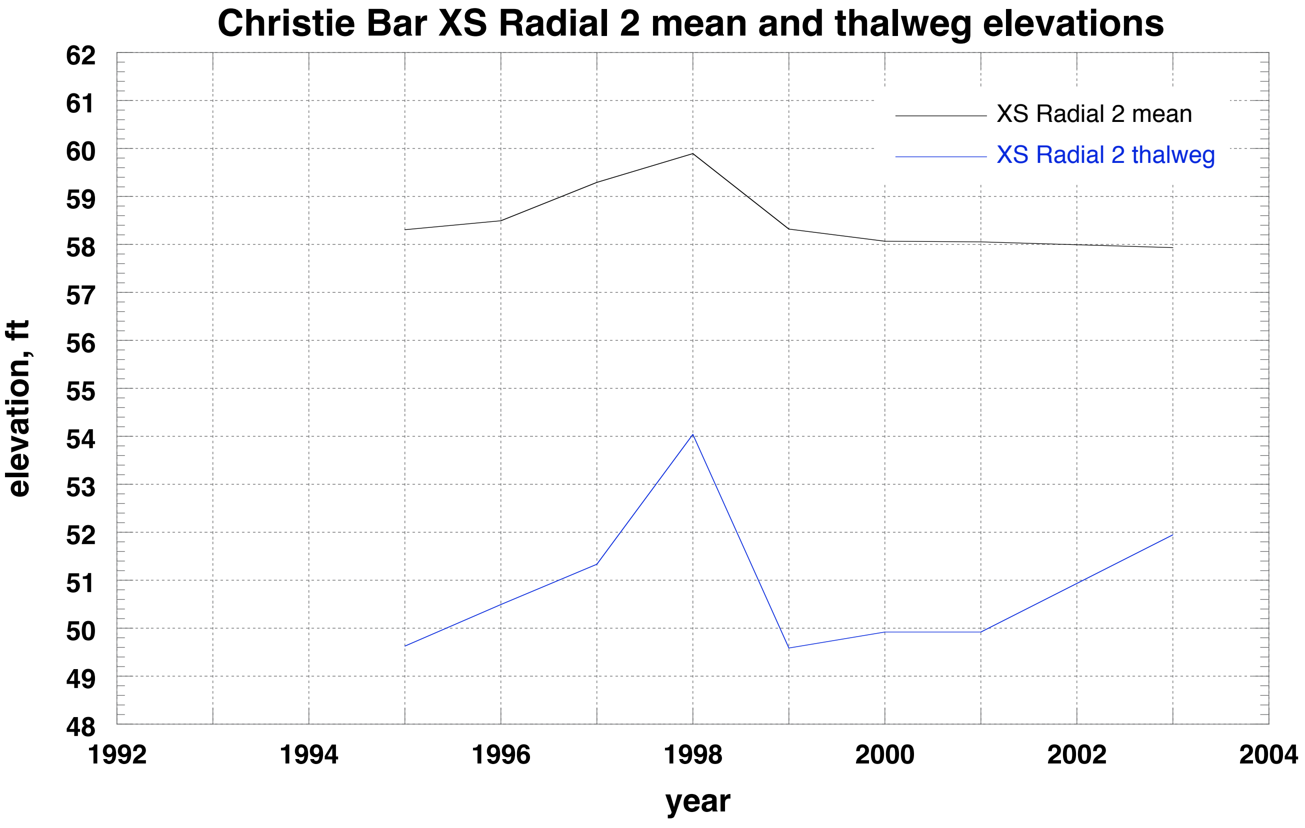
52
51
50
1992
1994
1996
1998
2000
2002
2004
year


Christie Bar XS Radial 2 mean and thalweg elevations
XS Radial 2 mean
XS Radial 2 thalweg
elevation, ft
62
61
60
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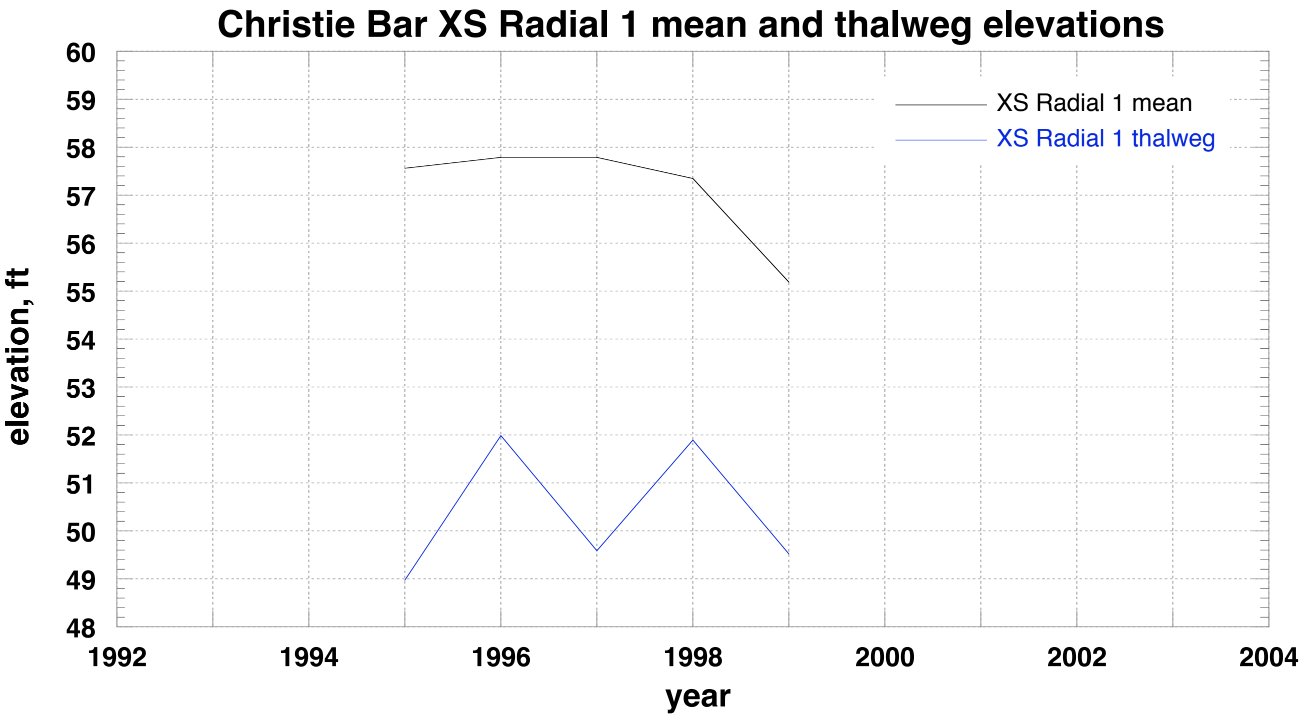
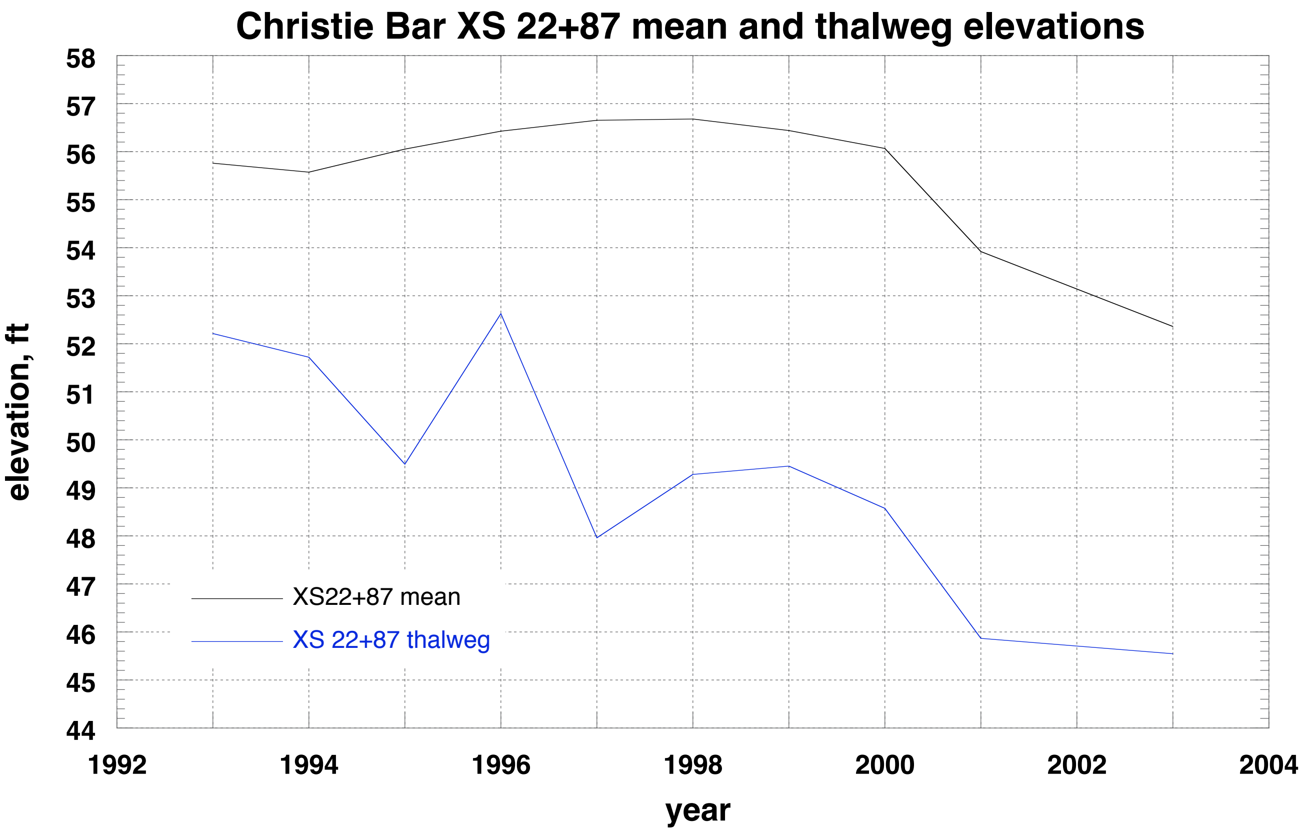
1994
1996
1998
2000
2002
2004
year


Christie Bar XS Radial 1 mean and thalweg elevations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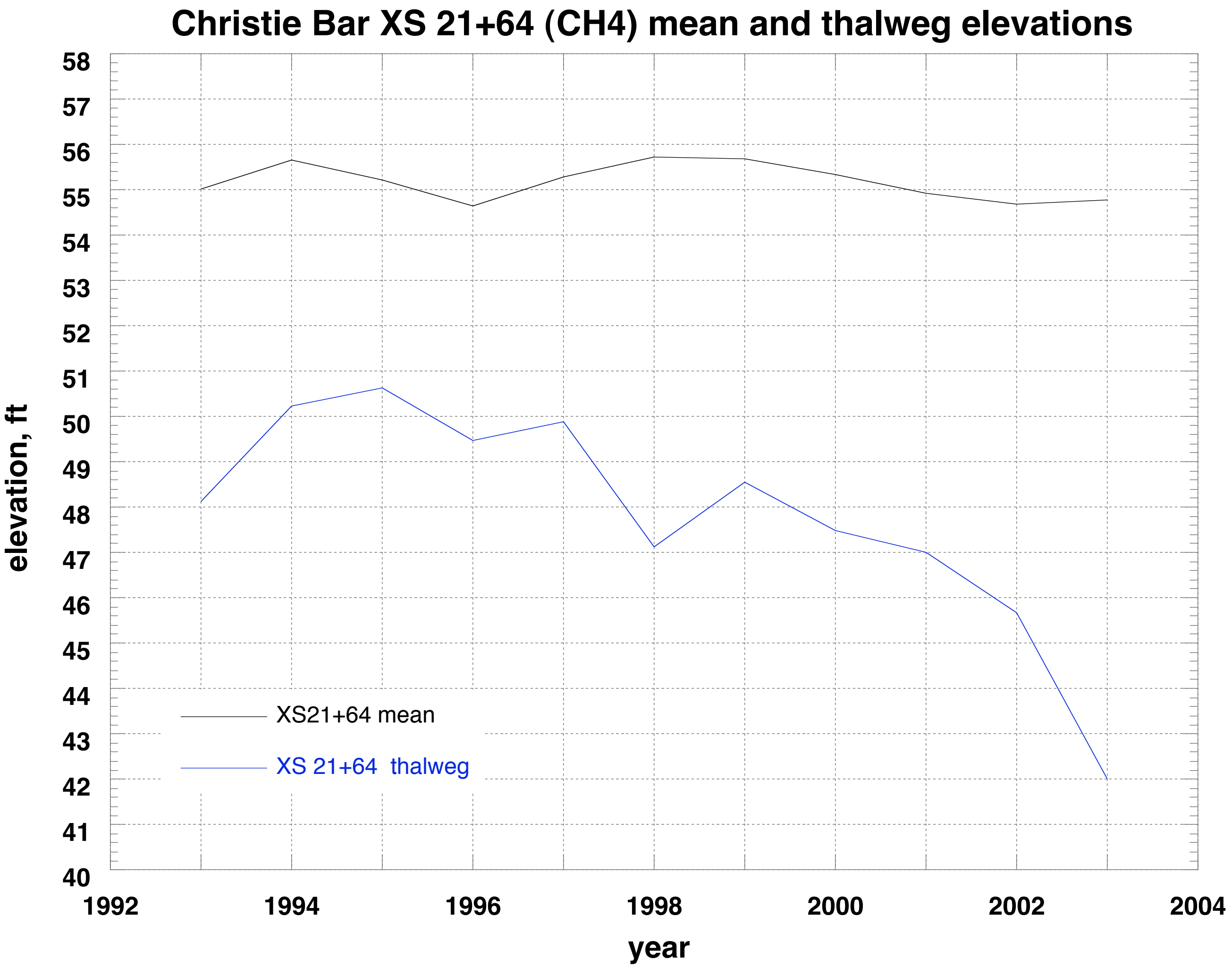
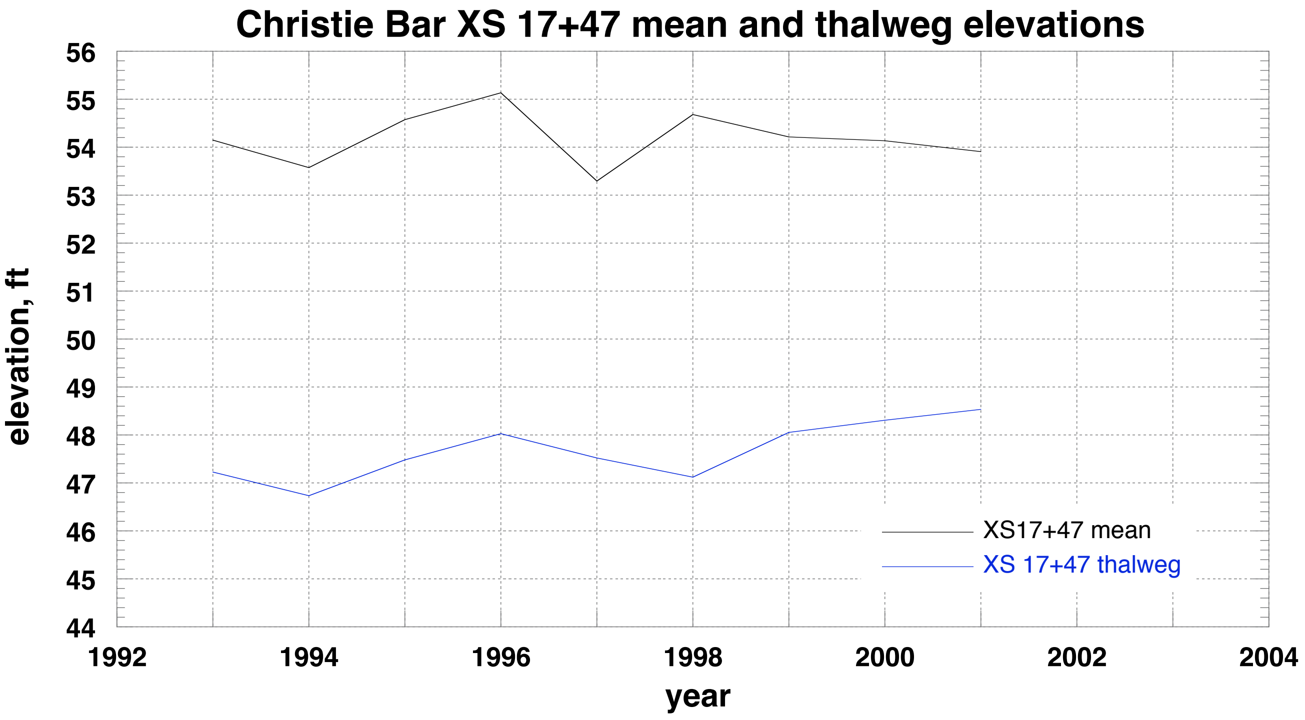
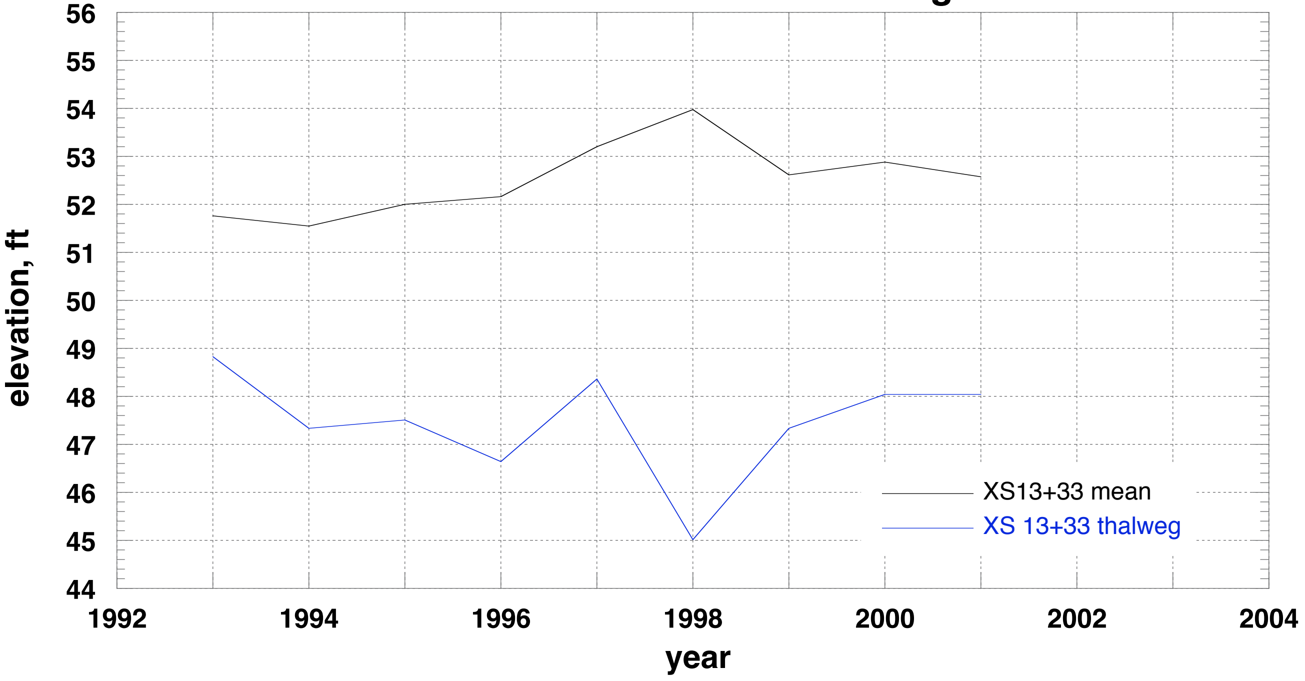
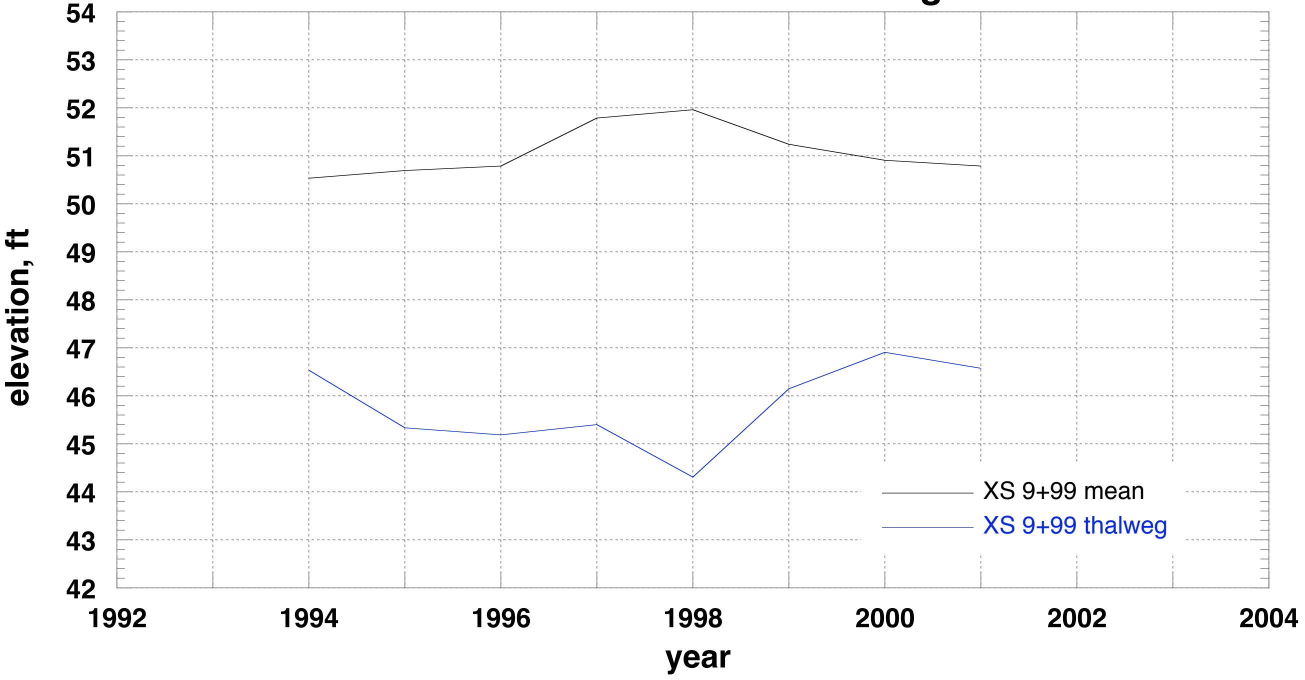

Christie Bar XS 21+64 (CH4) mean and thalweg elevations
58
57
56
55
54
53
52
51
50
49
48
47
46
45
44
43
42
41
40
elevation, ft
1992
1994
1996
1998
2000
2002
2004
year
XS21+64 mean
XS 21+64 thalweg

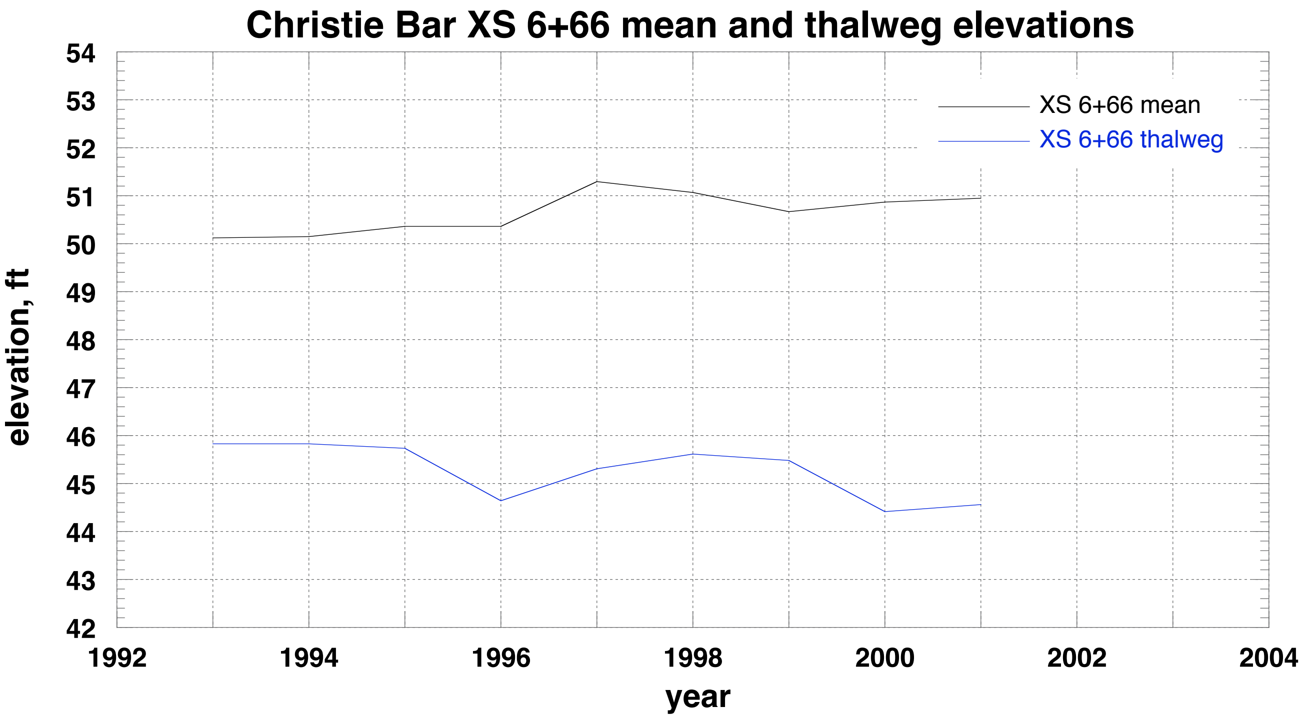

Christie Bar XS 17+47 mean and thalweg elevations
56
55
54
53
52
51
50
49
48
47
46
45
44
elevation, ft
1992
1994
1996
1998
2000
2002
2004
year
XS17+47 mean
XS 17+47 thalweg



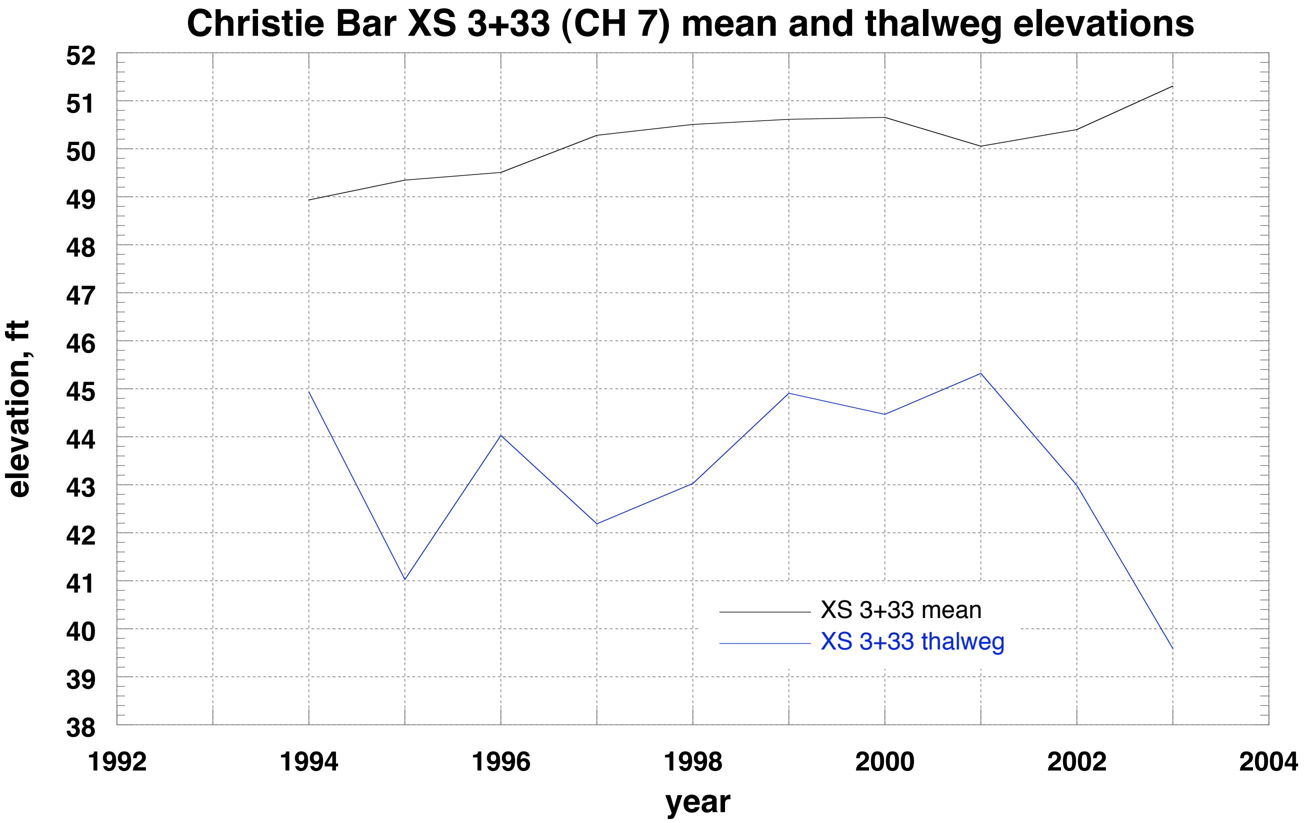
Christie Bar XS 13+33 mean and thalweg elevations



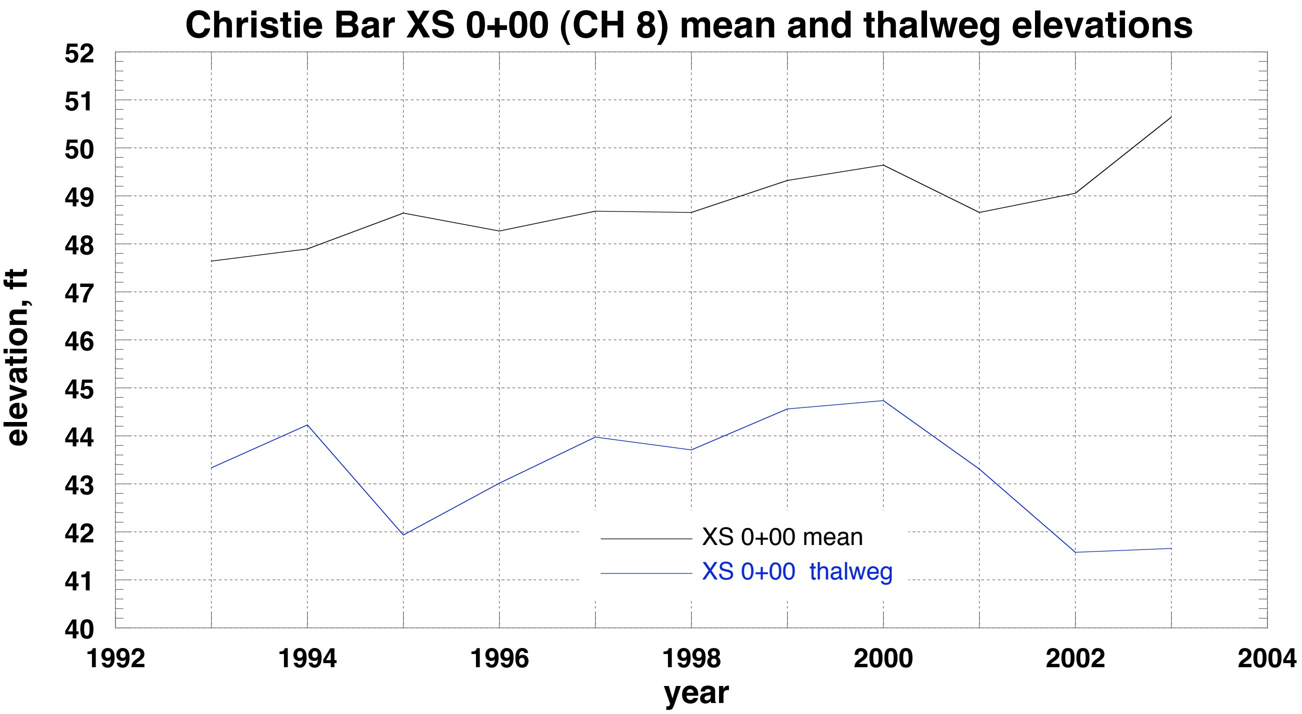
Christie Bar XS 9+99 mean and thalweg elevations

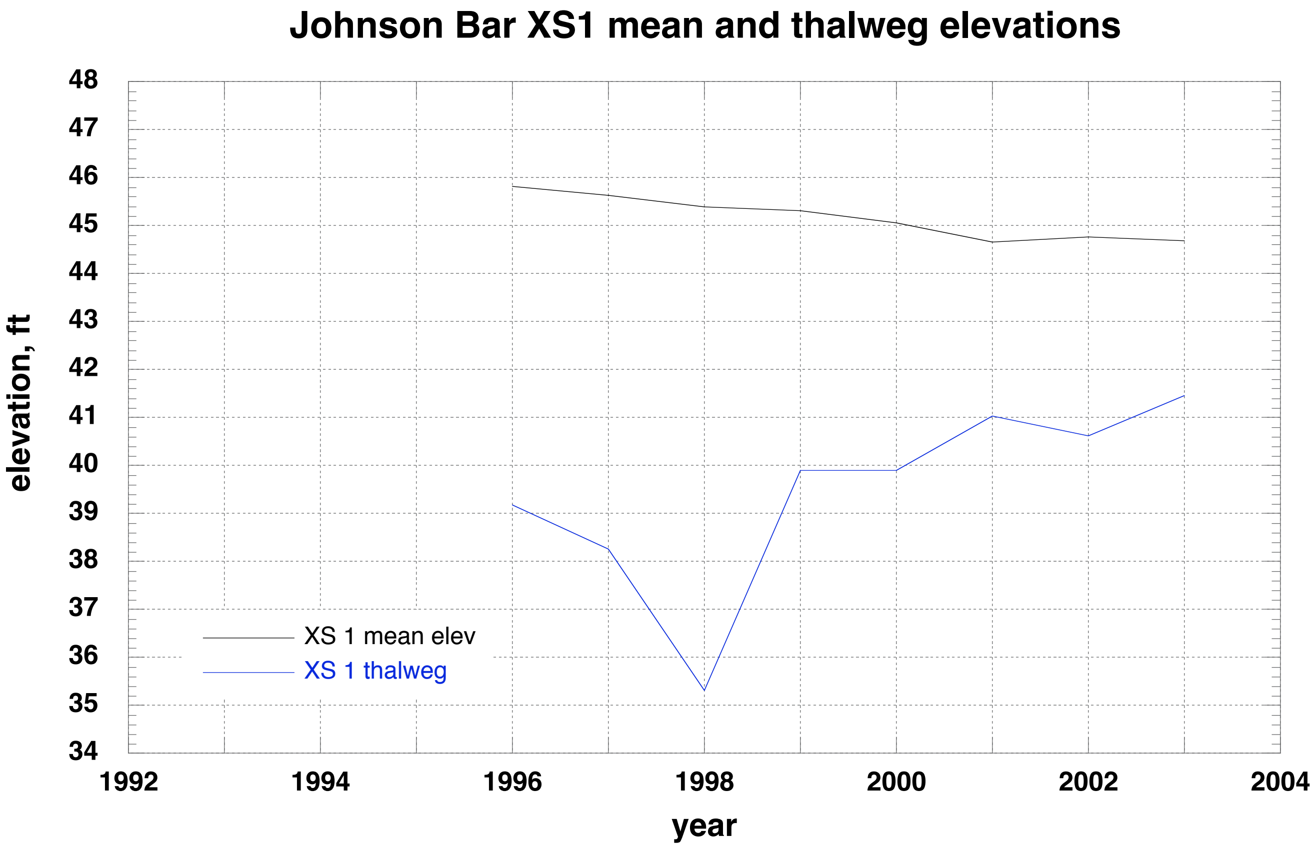


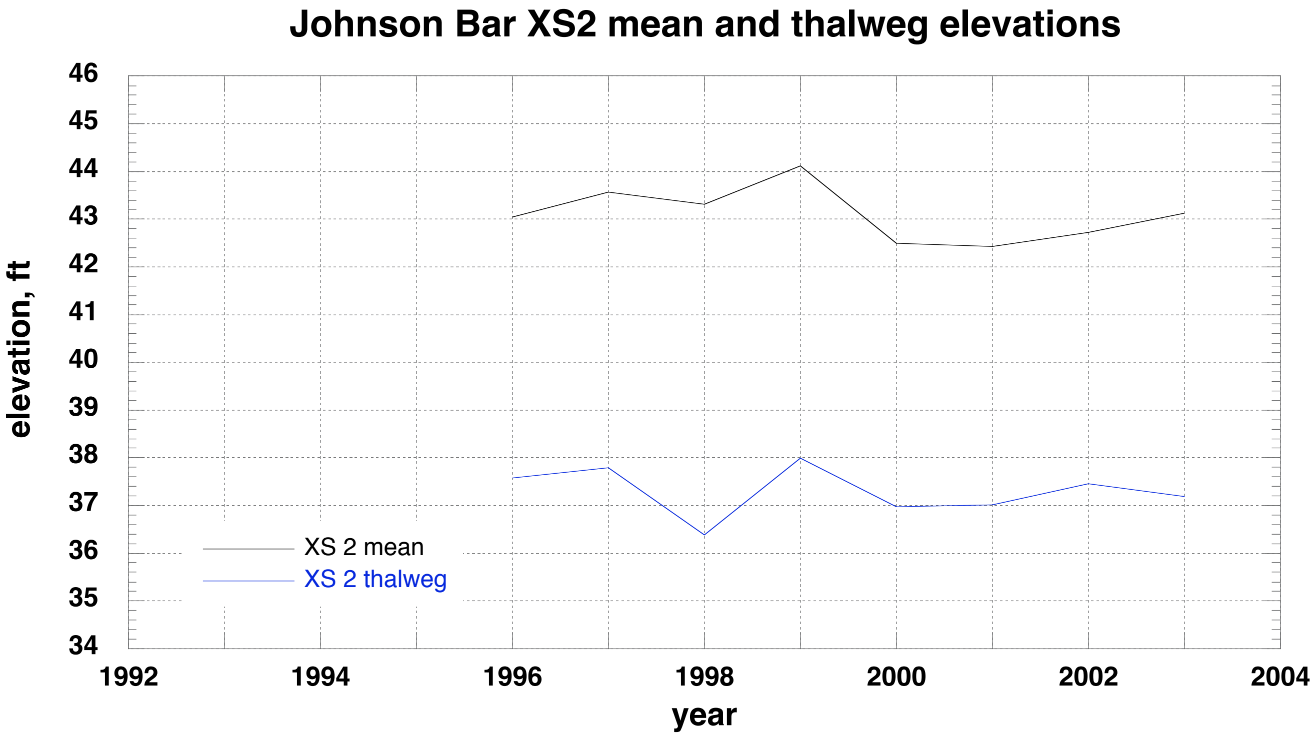
Christie Bar XS 6+66 mean and thalweg elevations

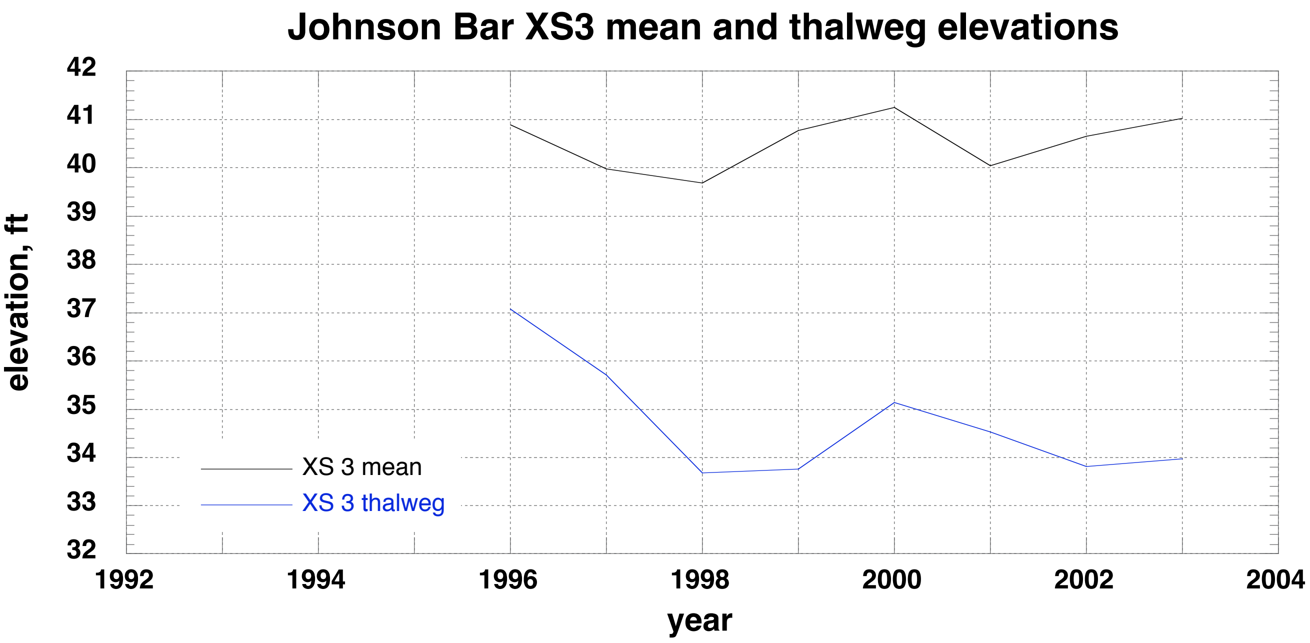


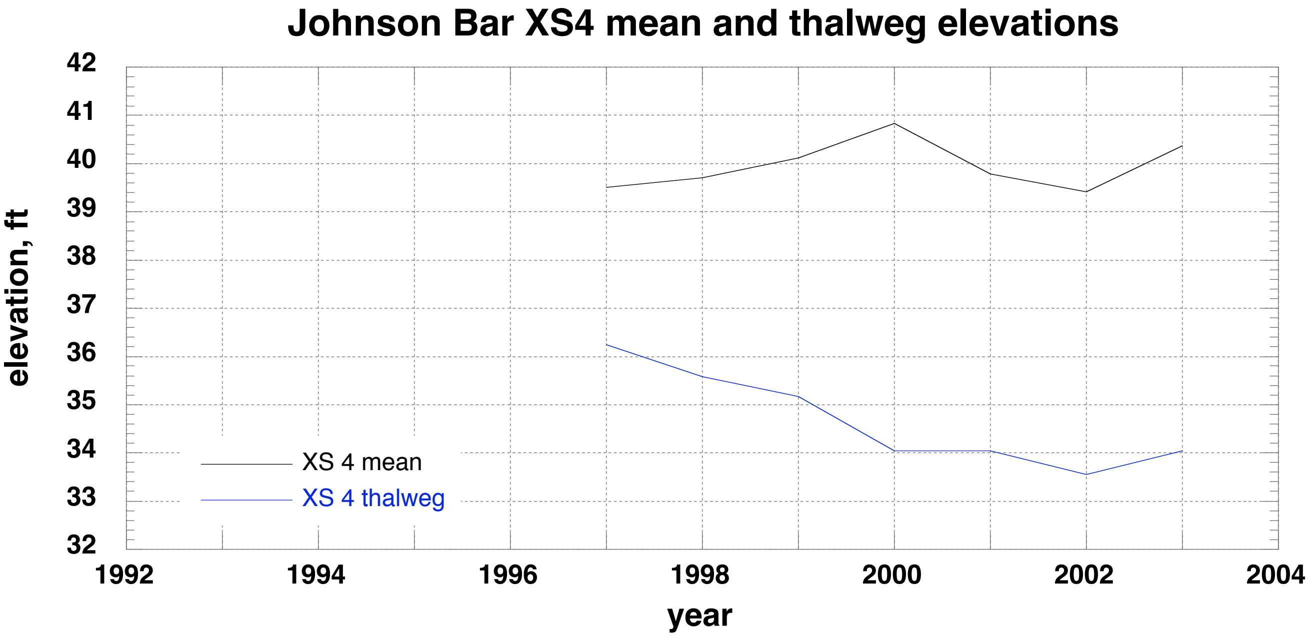
Christie Bar XS 3+33 (CH 7) mean and thalweg elevations

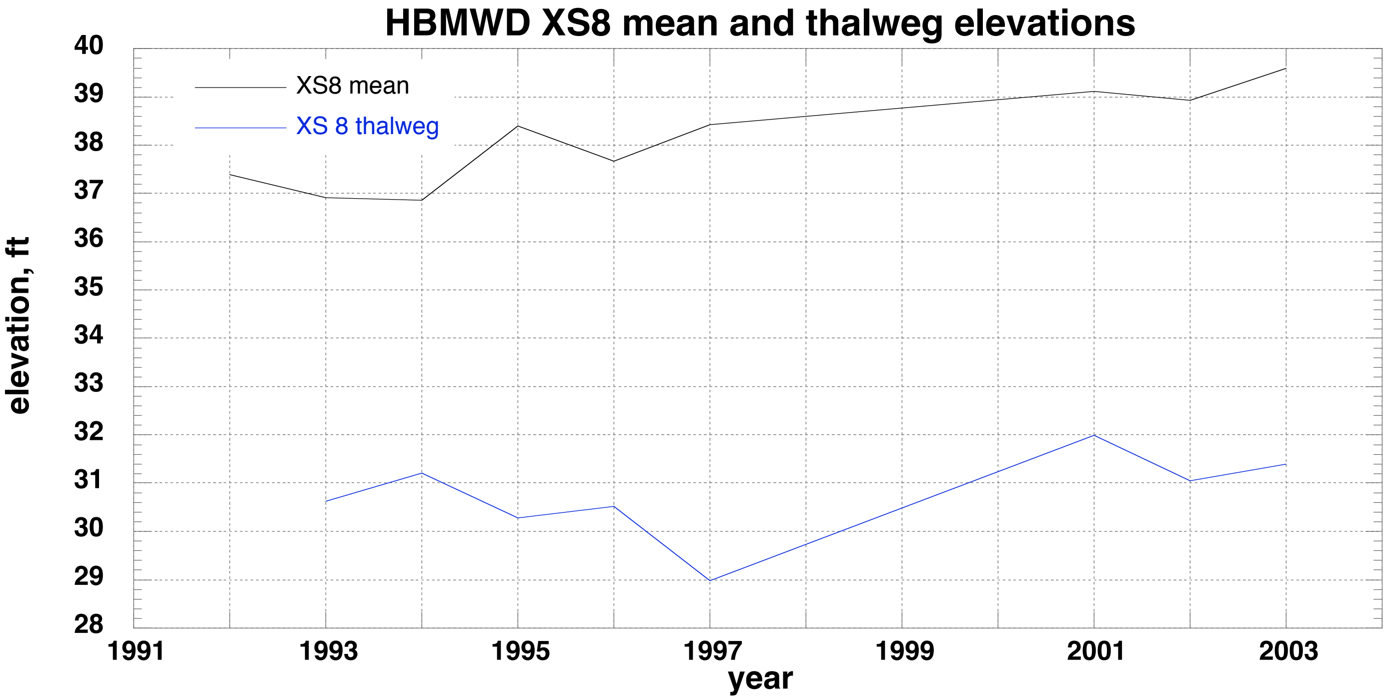

Christie Bar XS 0+00 (CH 8) mean and thalweg elevations

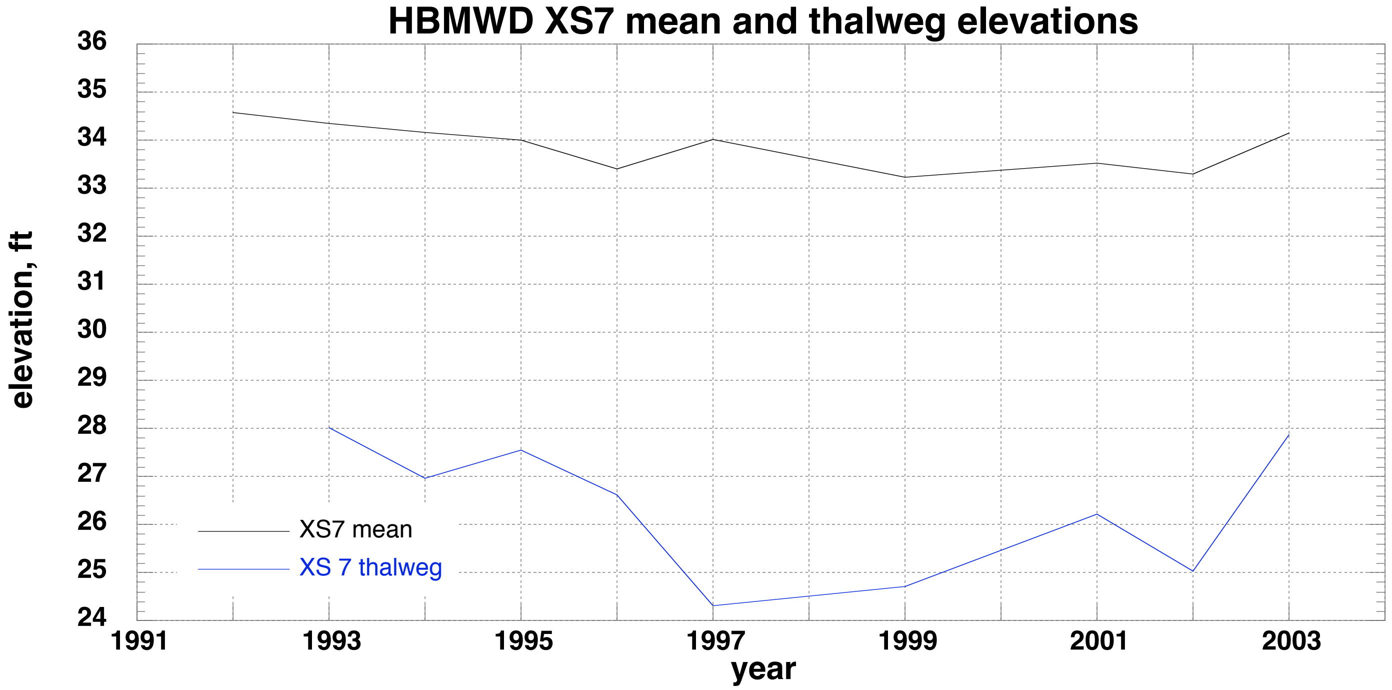

Johnson Bar XS1 mean and thalweg elevations

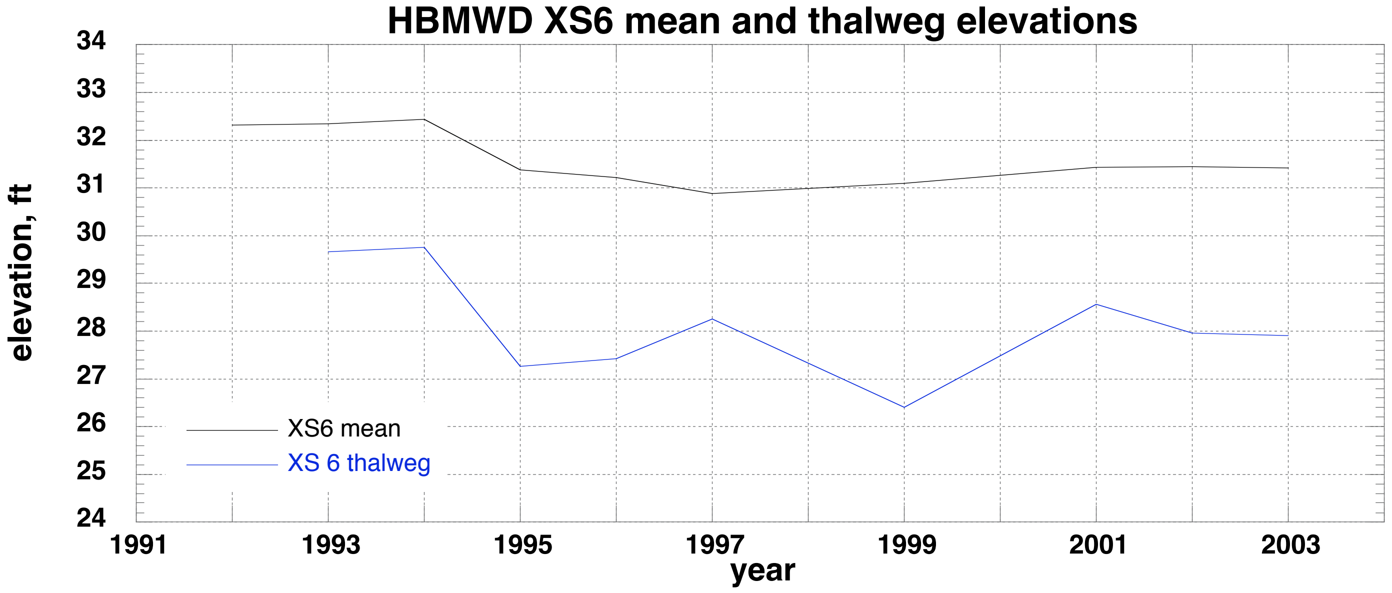

Johnson Bar XS2 mean and thalweg elevations

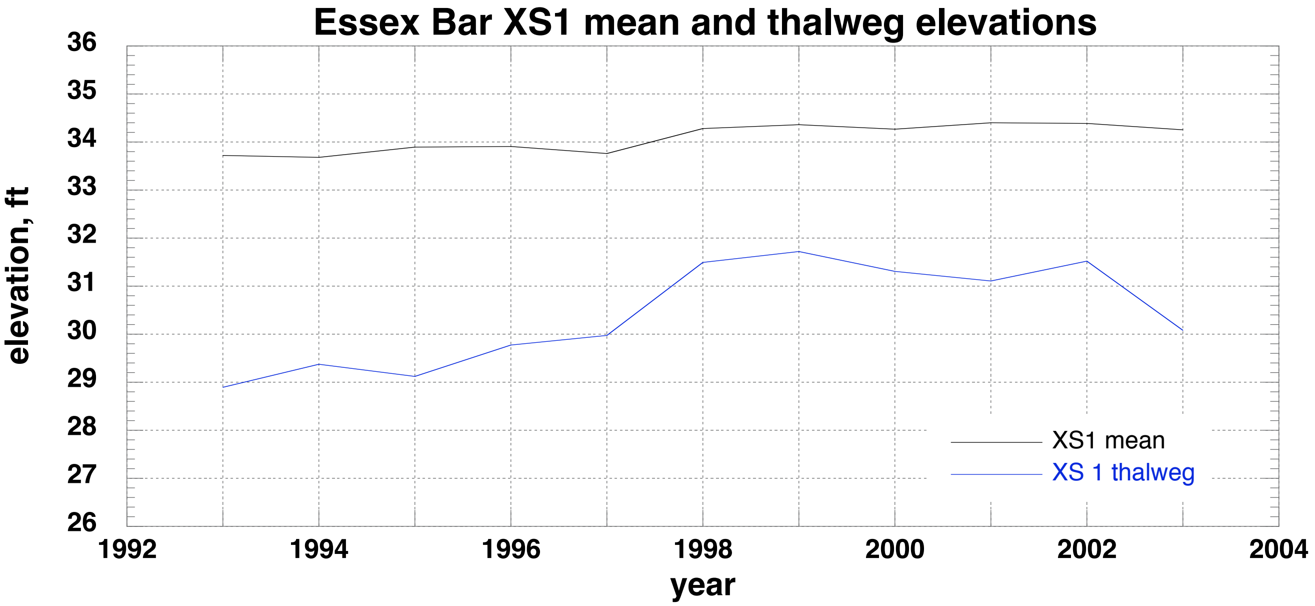

Johnson Bar XS3 mean and thalweg elevations


Johnson Bar XS4 mean and thalweg elevations

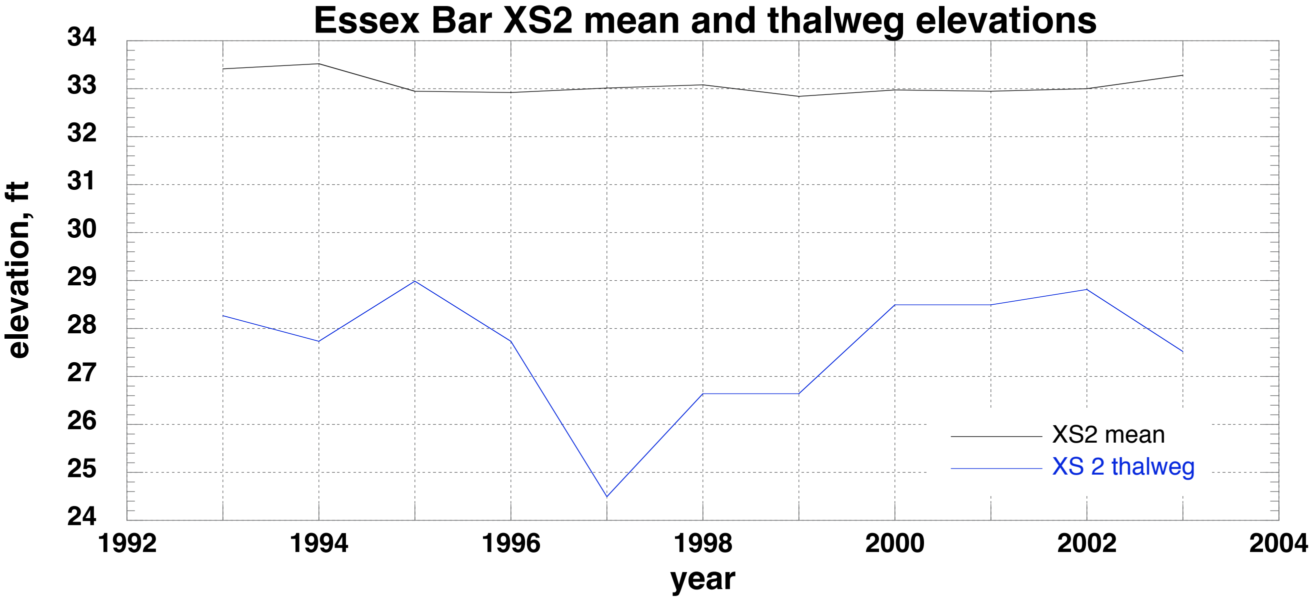

HBMWD XS8 mean and thalweg elevations
XS8 mean
XS 8 thalweg
elevation, ft
40
39
38
37
36
35
34
33
32
31
30
29
28
1991
1993
1995
1997
1999
2001
2003
year


HBMWD XS7 mean and thalweg elevations
XS7 mean
XS 7 thalweg
elevation, ft
36
35
34
33
32
31
30
29
28
27
26
25
24
1991
1993
1995
1997
1999
2001
2003
year

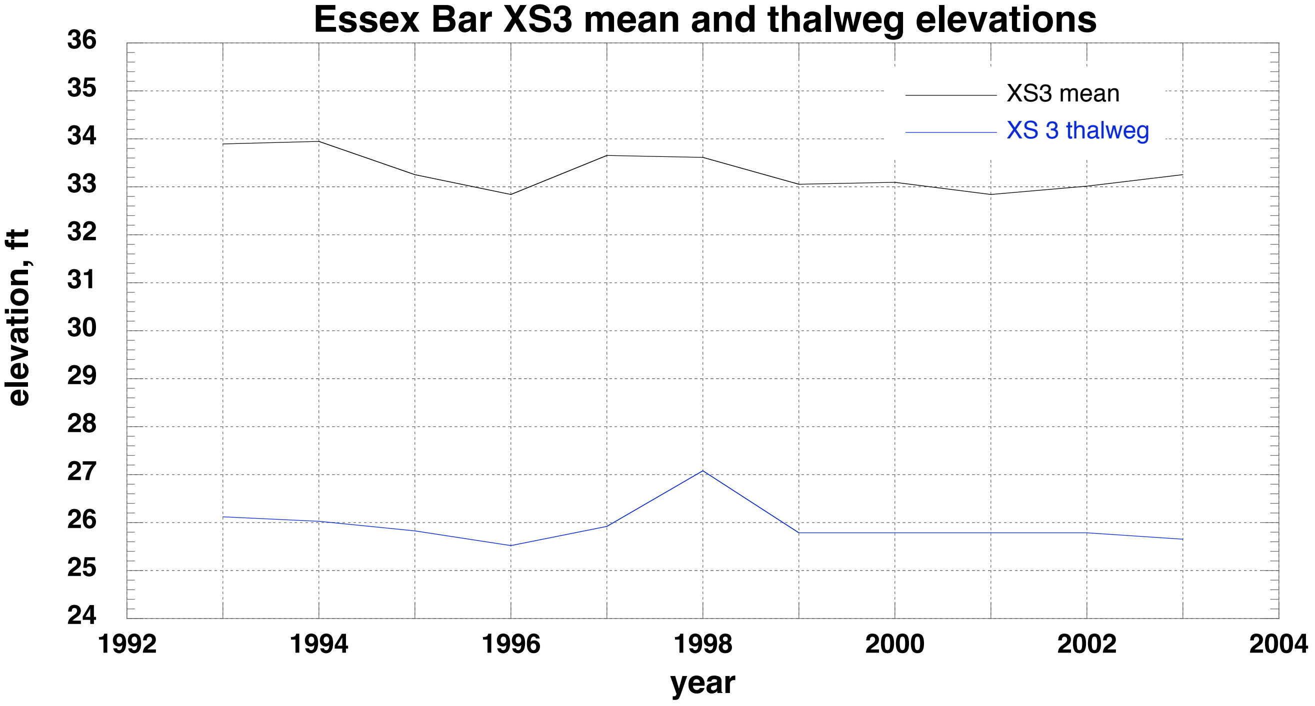

HBMWD XS6 mean and thalweg elevations
XS6 mean
XS 6 thalweg
elevation, ft
34
33
32
31
30
29
28
27
26
25
24
1991
1993
1995
1997
1999
2001
2003
year



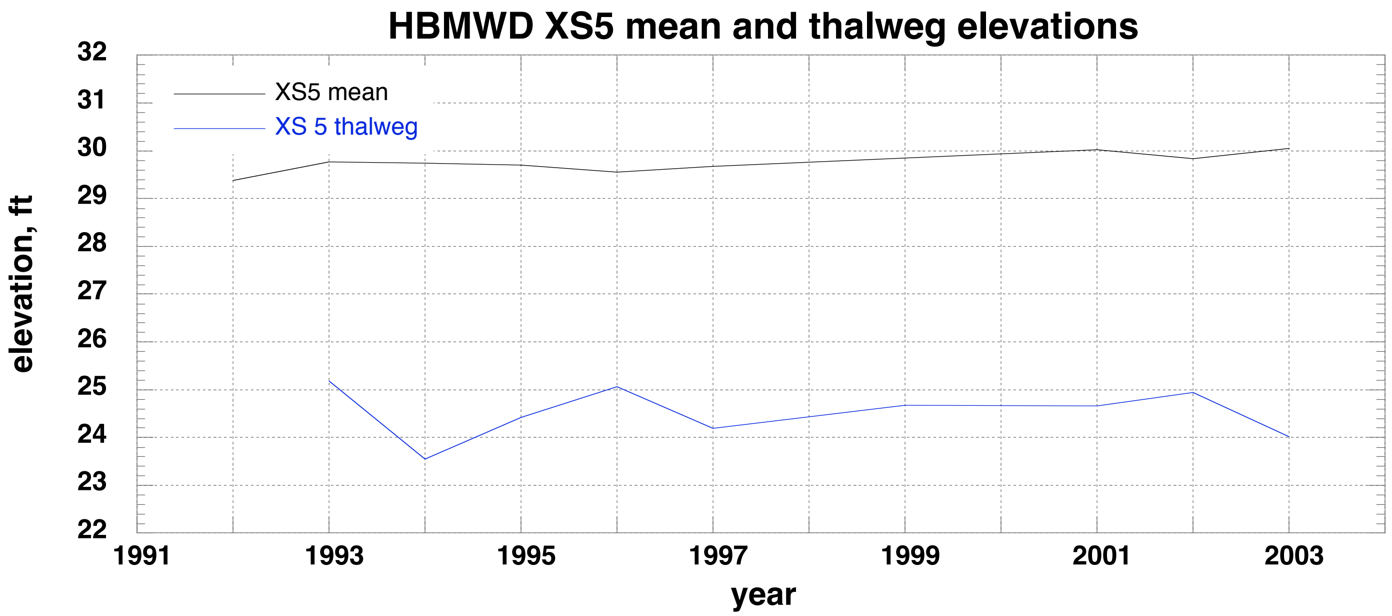
Essex Bar XS1 mean and thalweg elevations

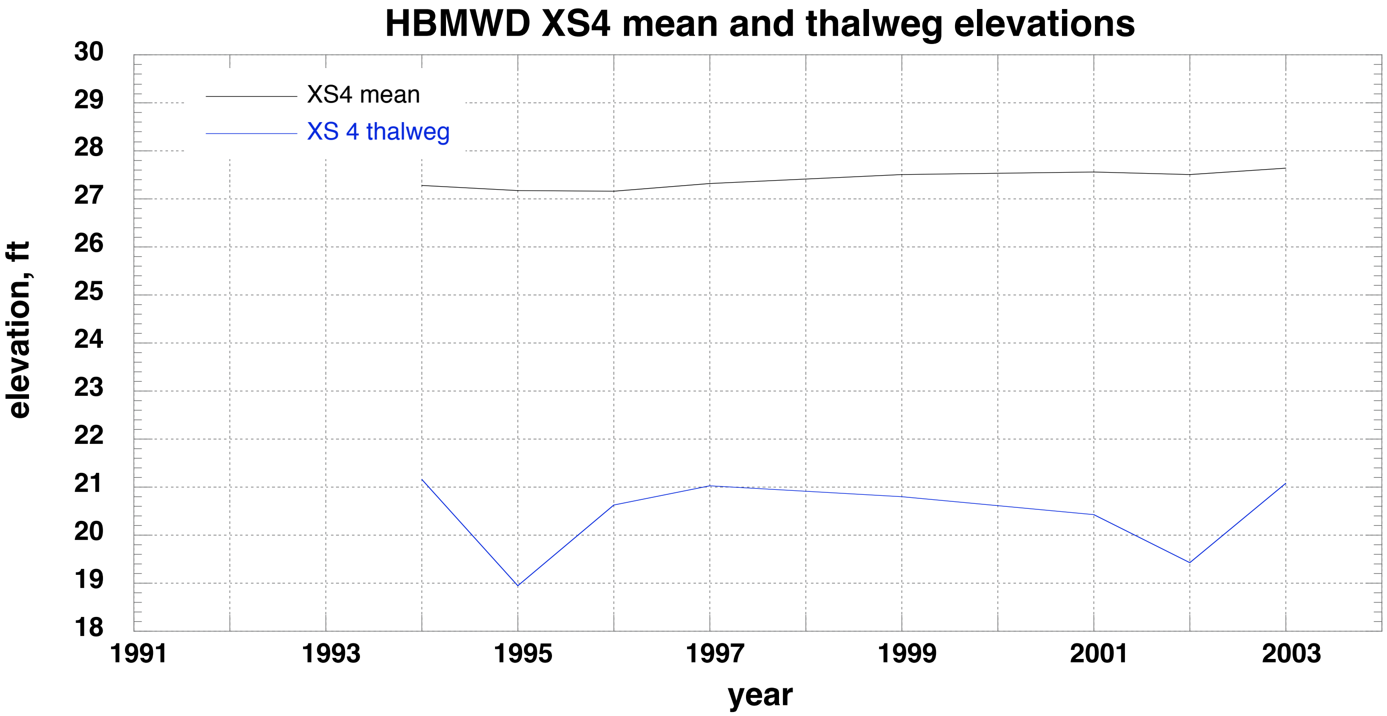


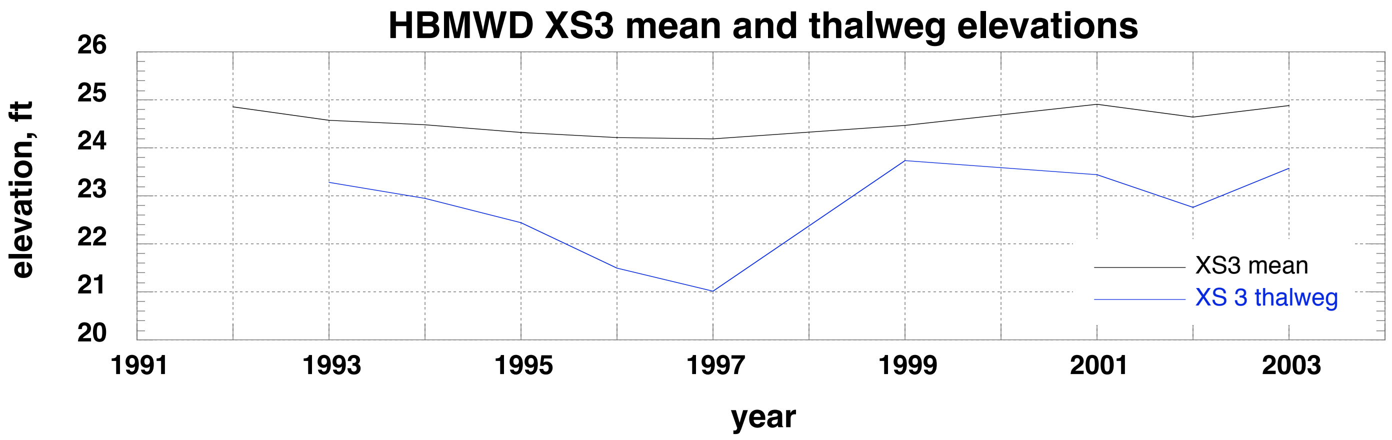
Essex Bar XS2 mean and thalweg elevations

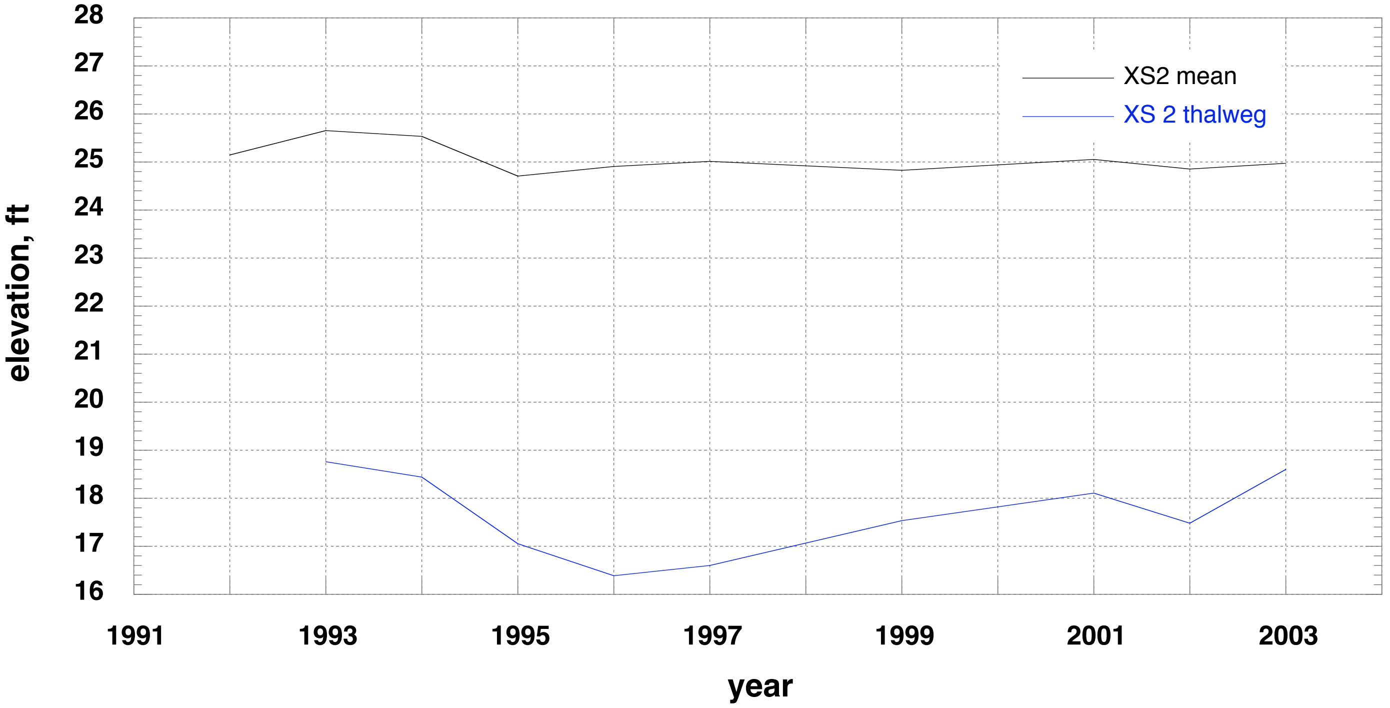


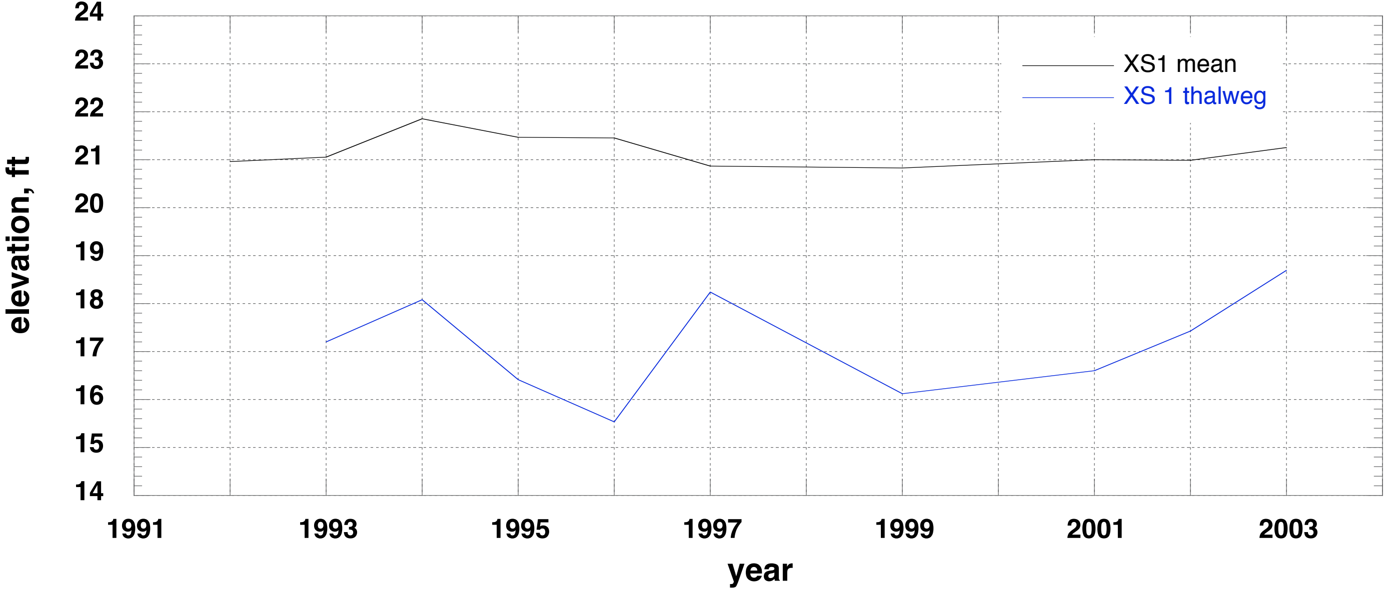
Essex Bar XS3 mean and thalweg elevations


HBMWD XS5 mean and thalweg elevations
XS5 mean
XS 5 thalweg
elevation, ft
32
31
30
29
28
27
26
25
24
23
22
1991
1993
1995
1997
1999
2001
2003
year

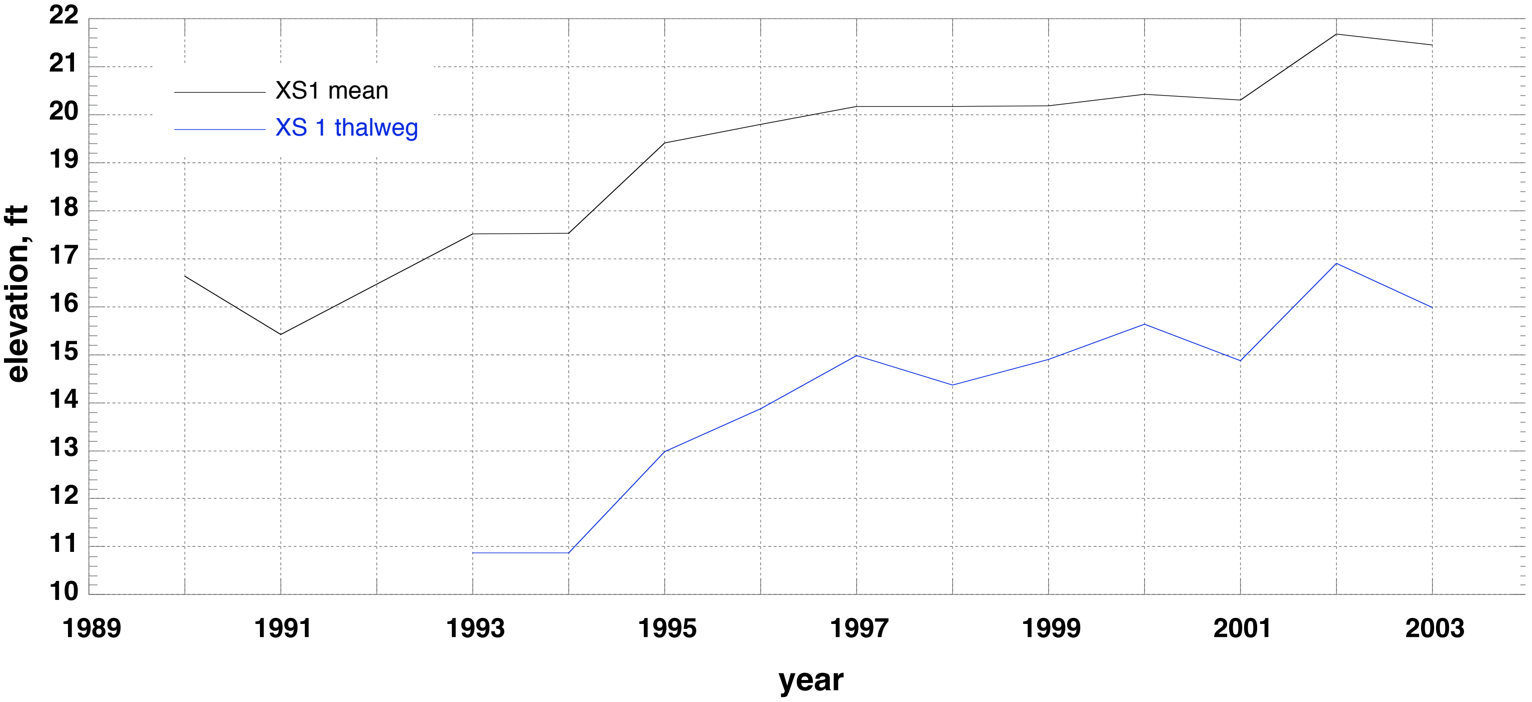

HBMWD XS4 mean and thalweg elevations
XS4 mean
XS 4 thalweg
elevation, ft
30
29
28
27
26
25
24
23
22
21
20
19
18
1991
1993
1995
1997
1999
2001
2003
year


HBMWD XS3 mean and thalweg elevations
XS3 mean
XS 3 thalweg
elevation, ft
26
25
24
23
22
21
20
1991
1993
1995
1997
1999
2001
2003
year

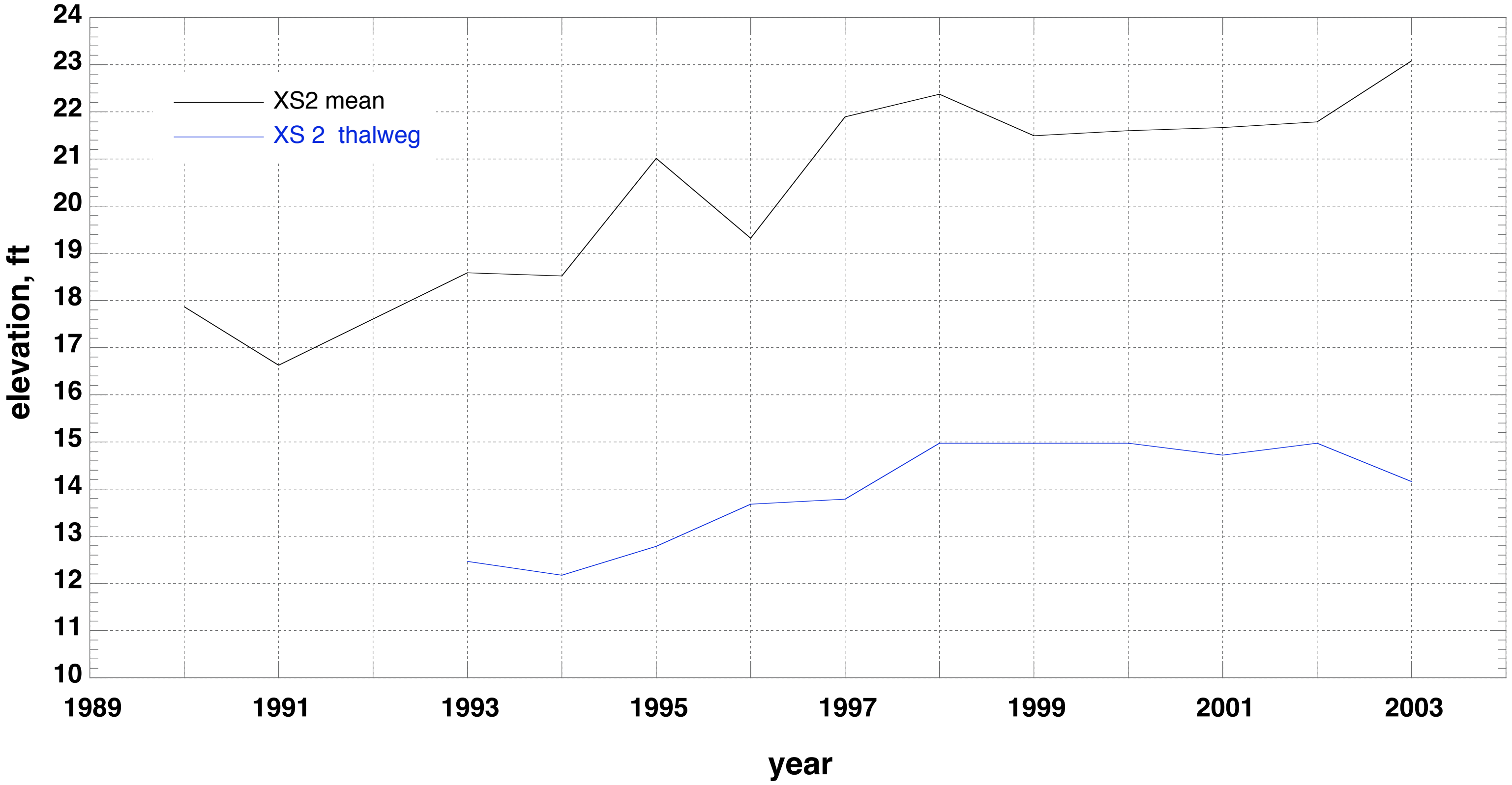

HBMWD XS2 mean and thalweg elevations


HBMWD XS1 mean and thalweg elevations

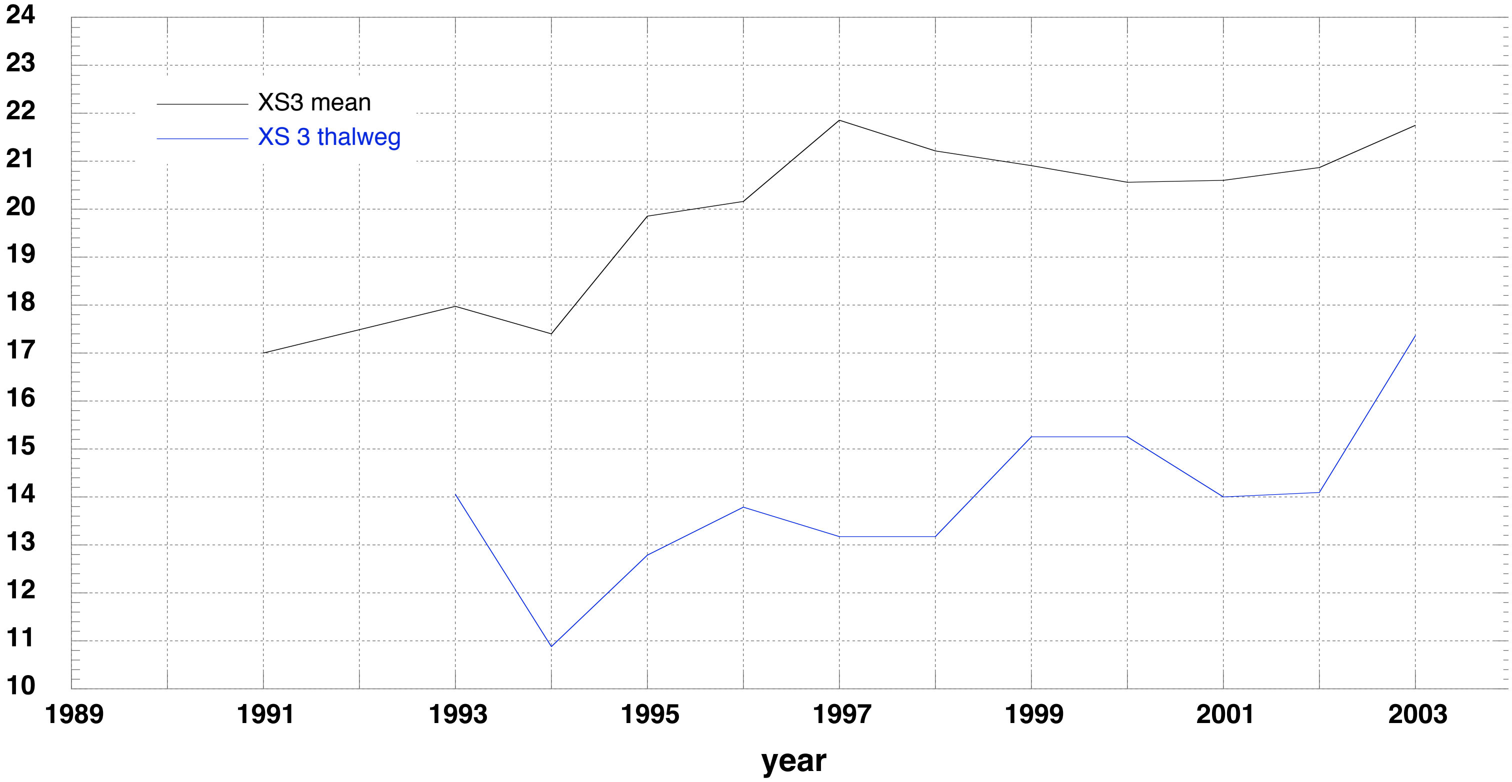
Johnson-Spini Bar XS1 mean and thalweg elevations



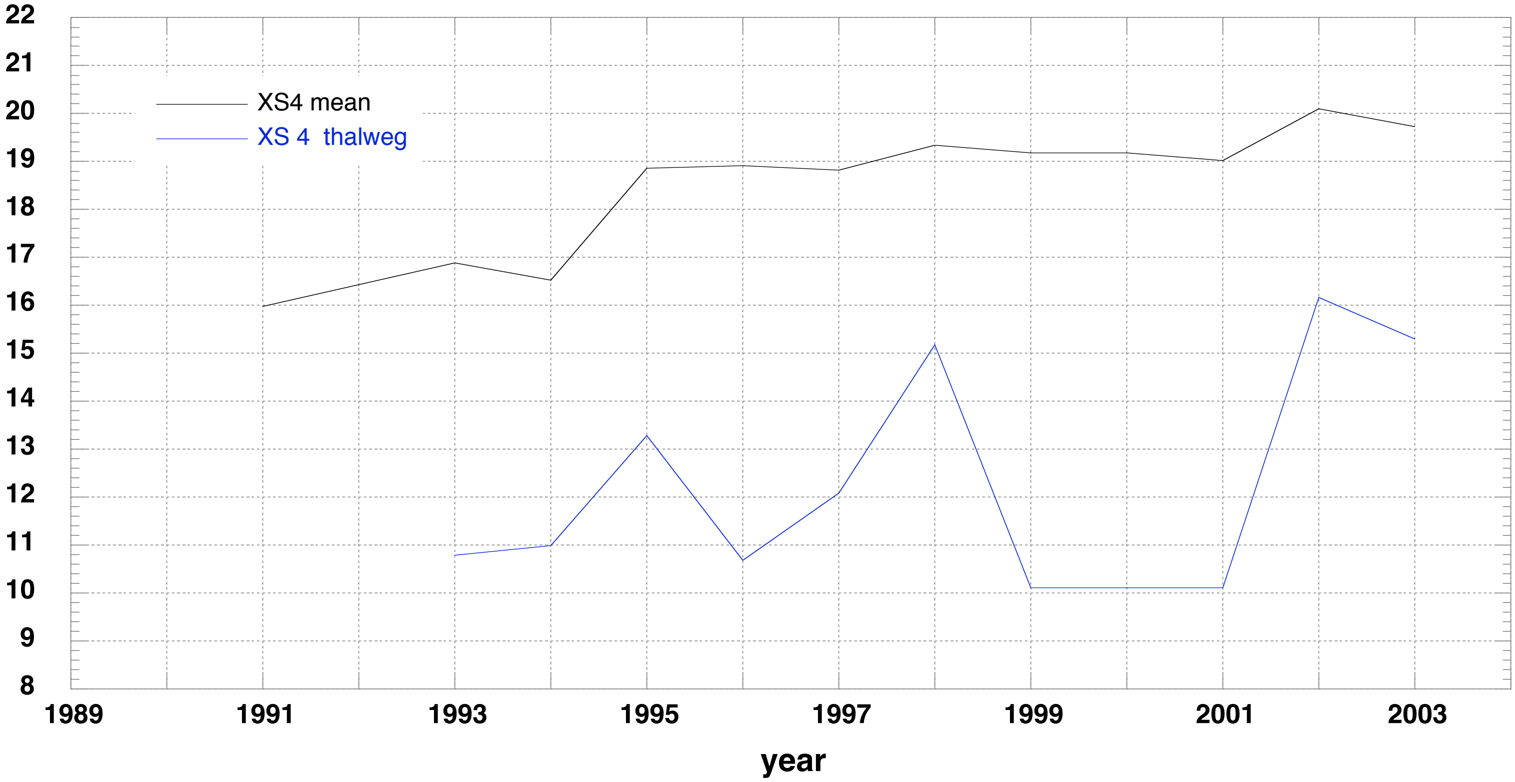
Johnson-Spini Bar XS2 mean and thalweg elevations

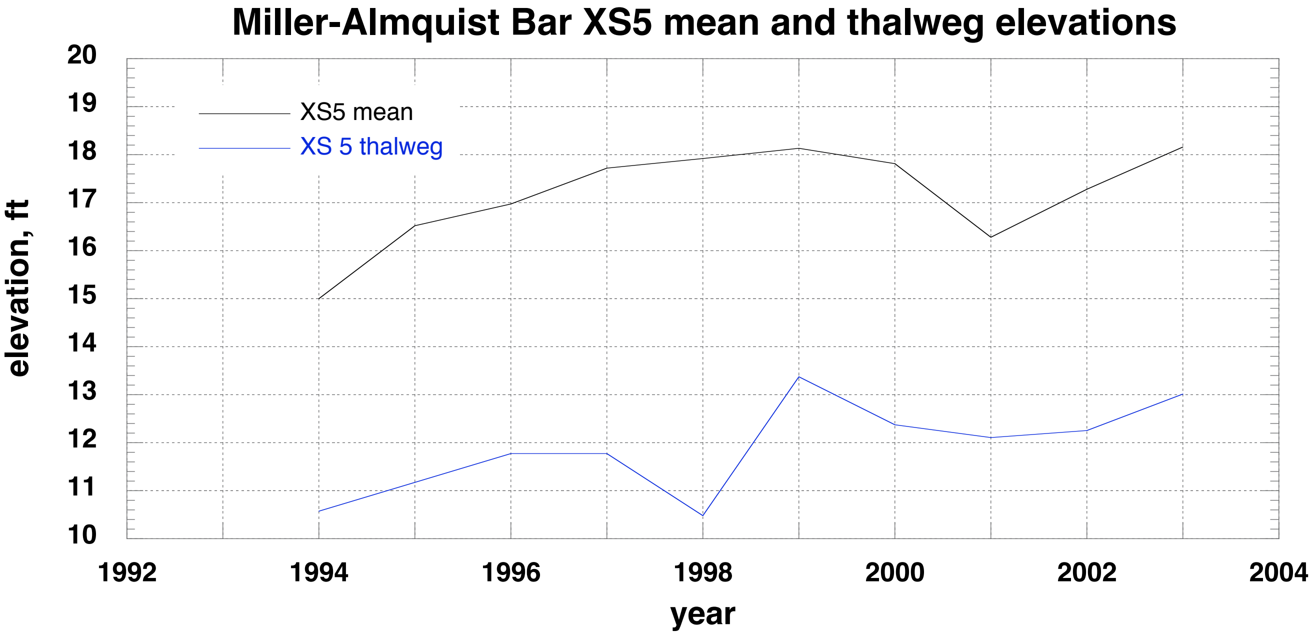


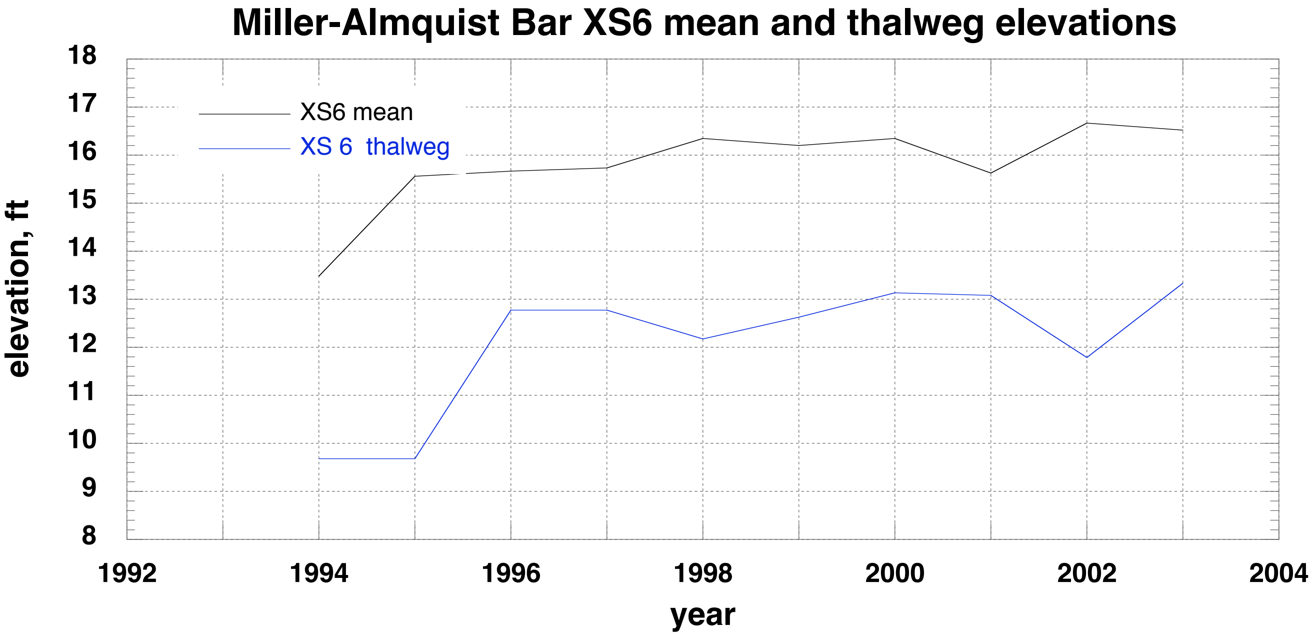
Johnson-Spini Bar XS3 mean and thalweg elevations

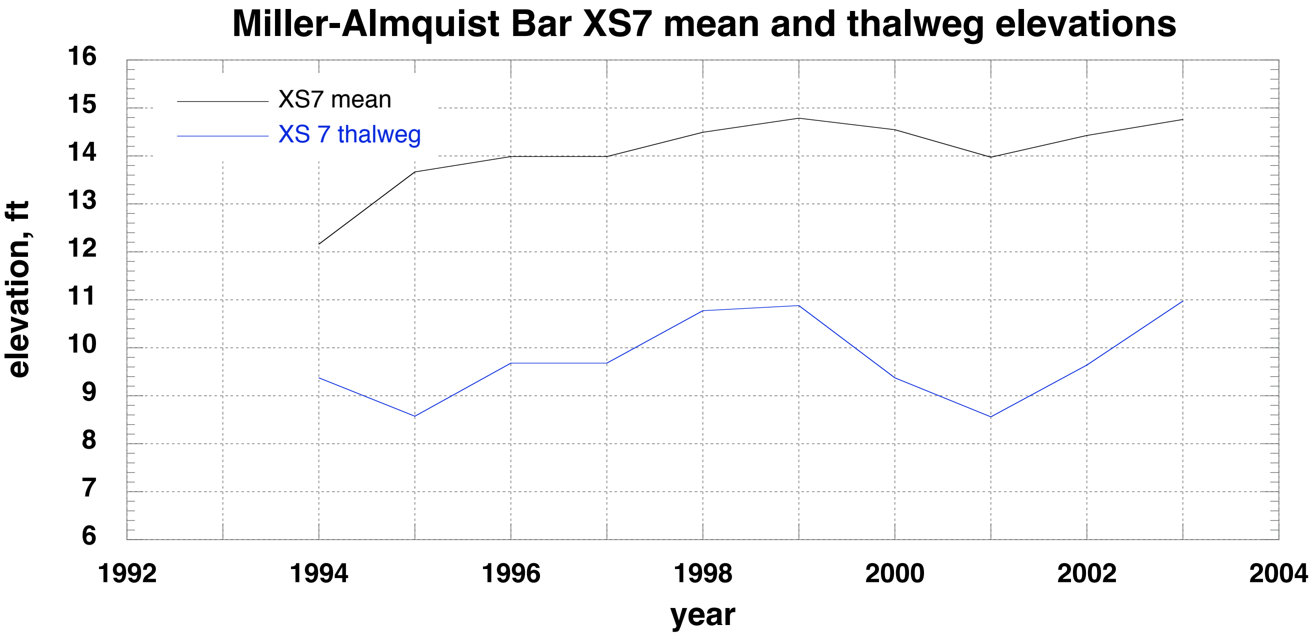


Johnson-Spini Bar XS4 mean and thalweg elevations

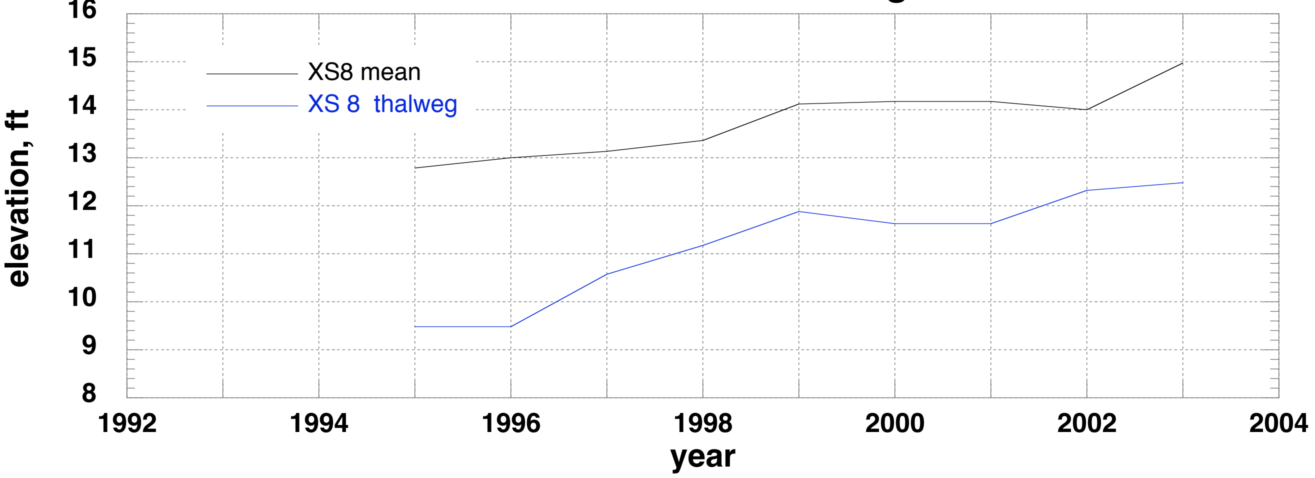



Miller-Almquist Bar XS5 mean and thalweg elevations
XS5 mean
XS 5 thalweg
elevation, ft
20
19
18
17
16
15
14
13
12
11
10
1992
1994
1996
1998
2000
2002
2004
year

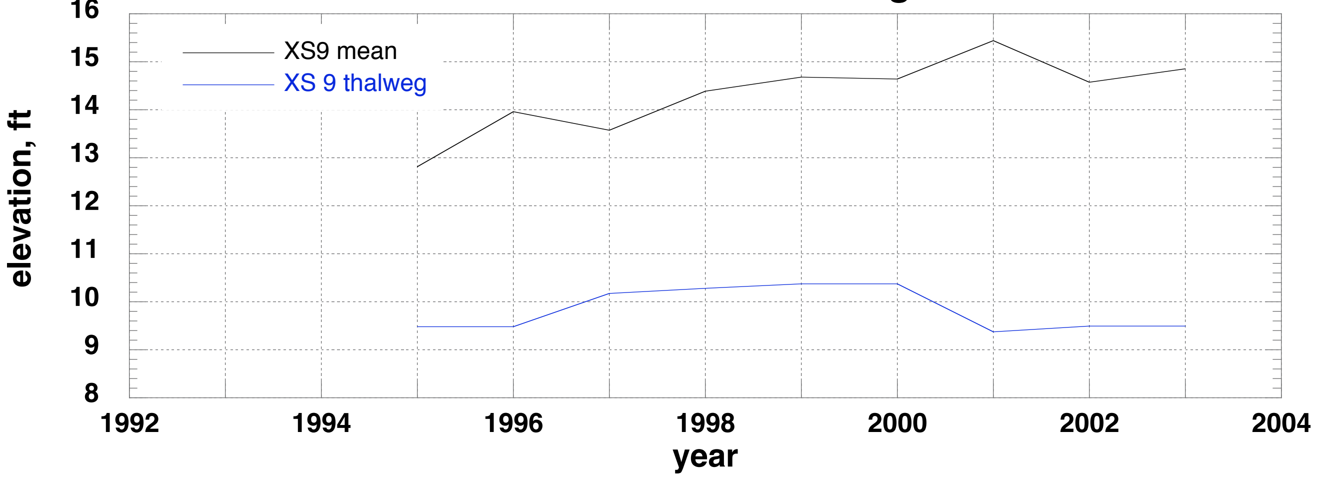

Miller-Almquist Bar XS6 mean and thalweg elevations
XS6 mean
XS 6 thalweg
elevation, ft
18
17
16
15
14
13
12
11
10
9
8
1992
1994
1996
1998
2000
2002
2004
year


Miller-Almquist Bar XS7 mean and thalweg elevations
XS7 mean
XS 7 thalweg
elevation, ft
16
15
14
13
12
11
10
9
8
7
6
1992
1994
1996
1998
2000
2002
2004
year

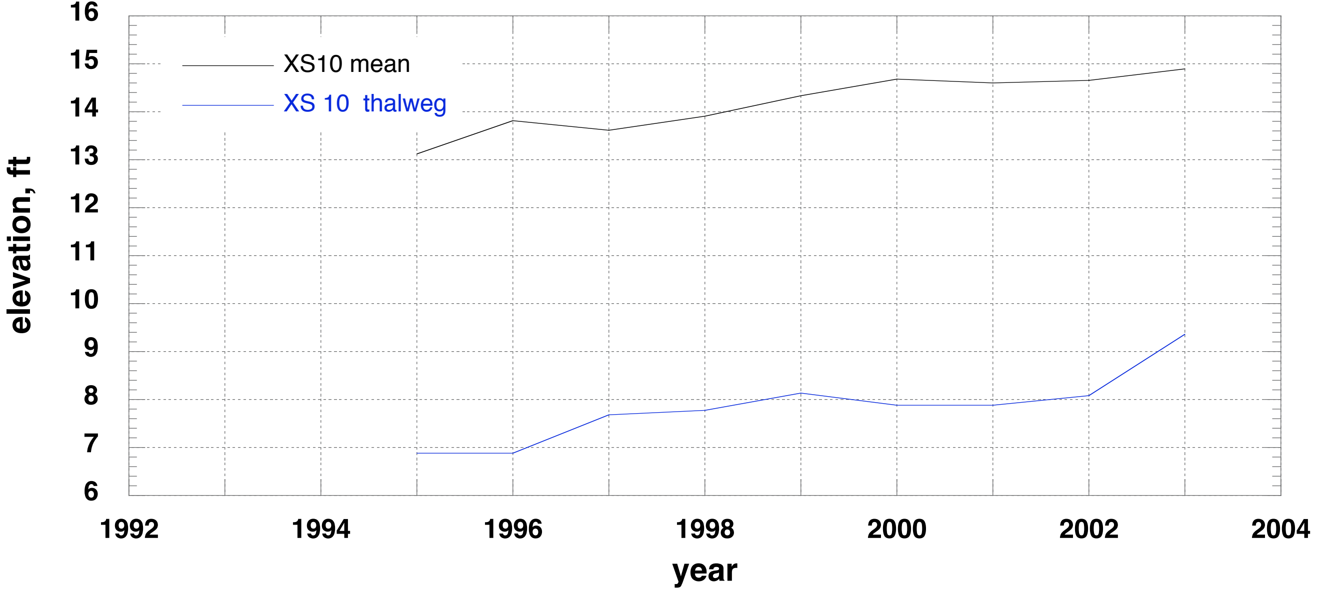
O'Neill Bar XS8 mean and thalweg elevations



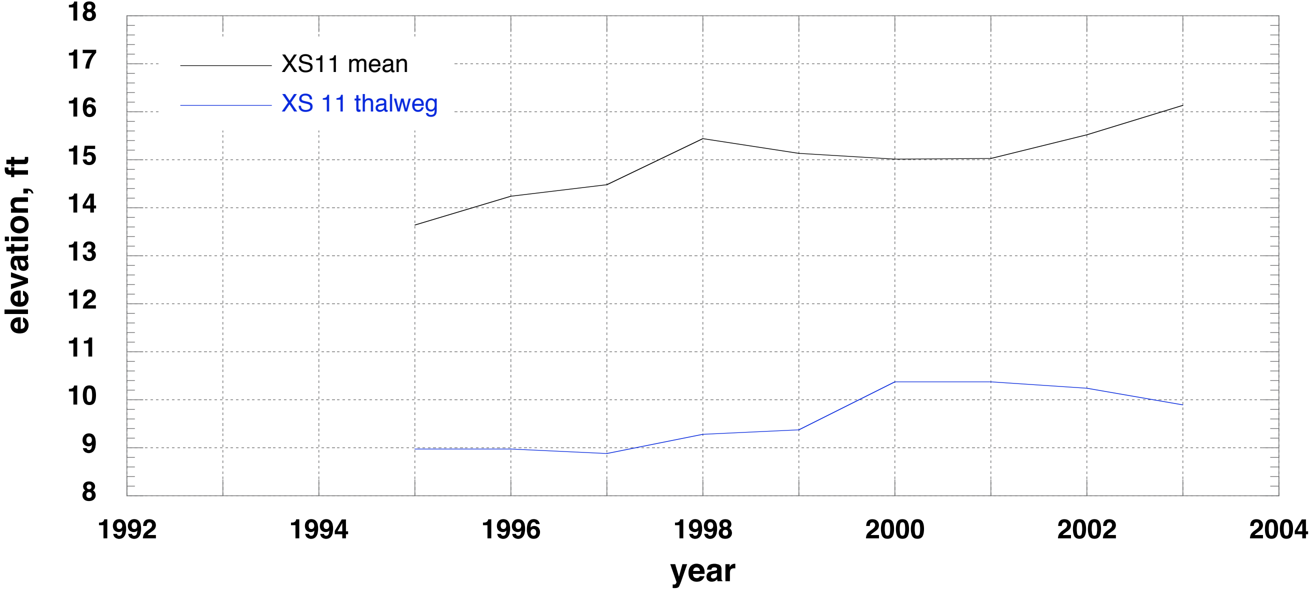
O'Neill Bar XS9 mean and thalweg elevations



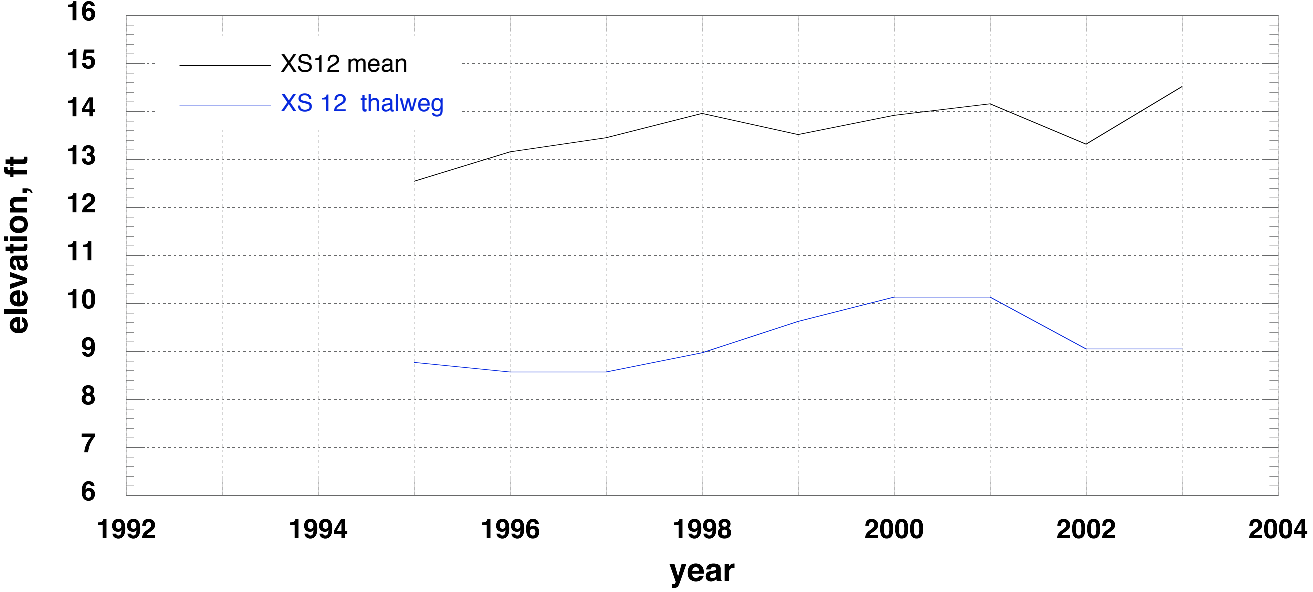
O'Neill Bar XS10 mean and thalweg elevations



O'Neill Bar XS11 mean and thalweg elevations



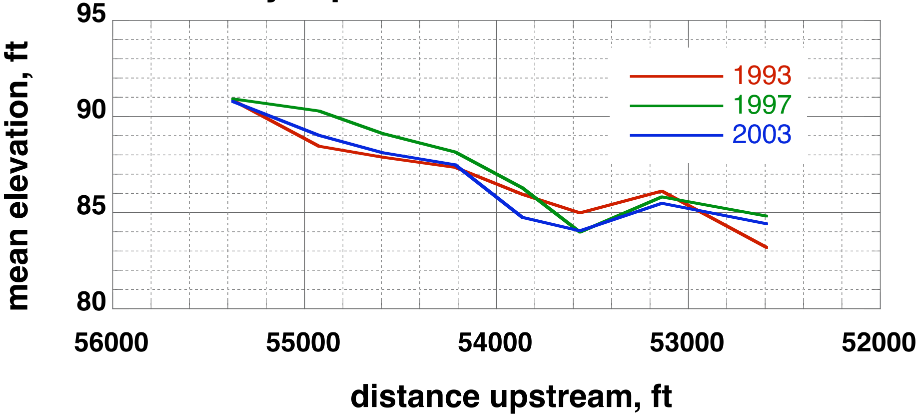
O'Neill Bar XS12 mean and thalweg elevations



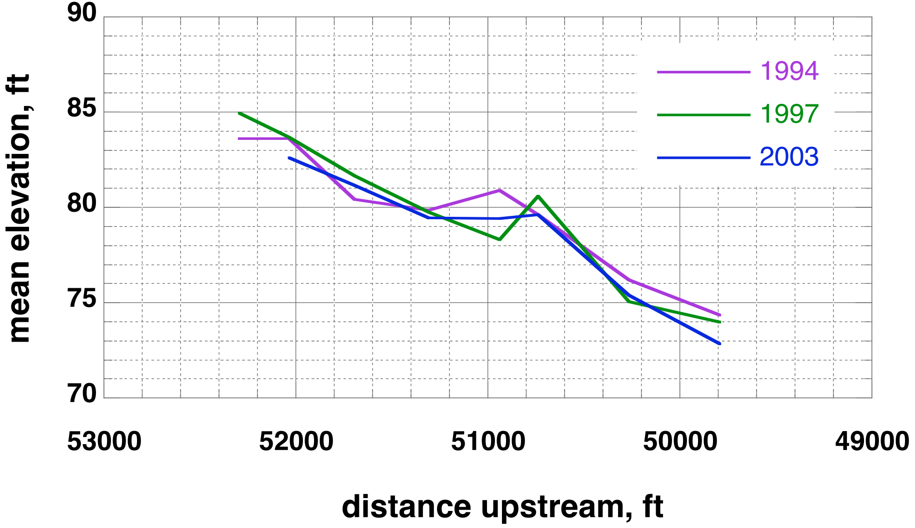
Appendix B

XS mean elevation vs streamwise distance, by bars
1993, 1997, 2003

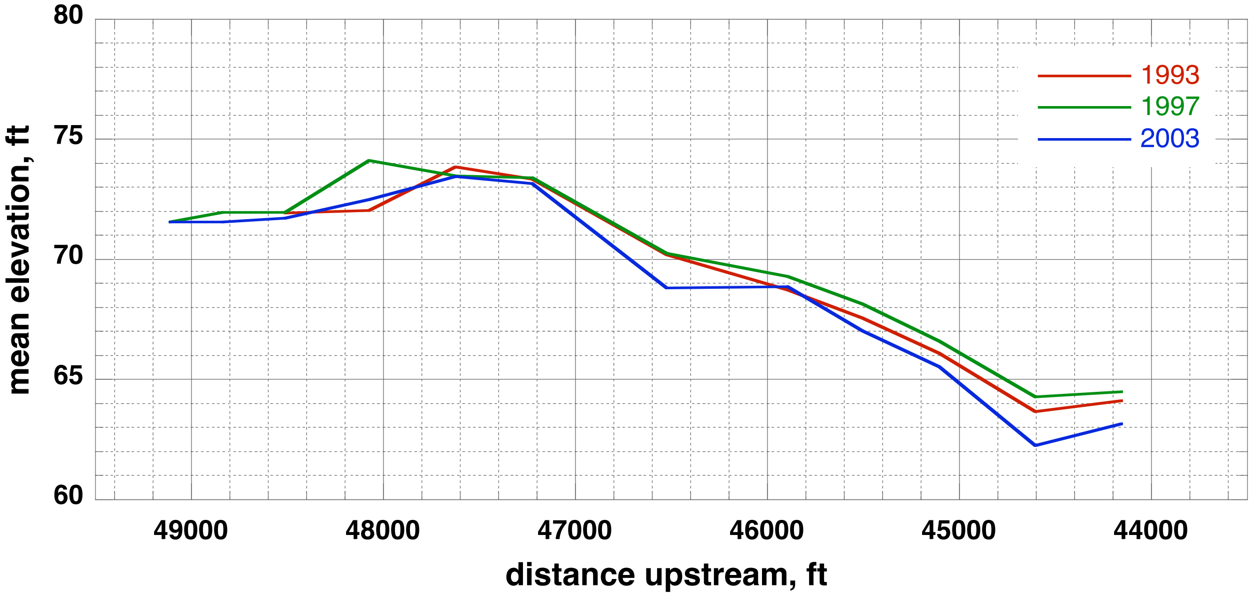
Guynup Bar mean XS elevations

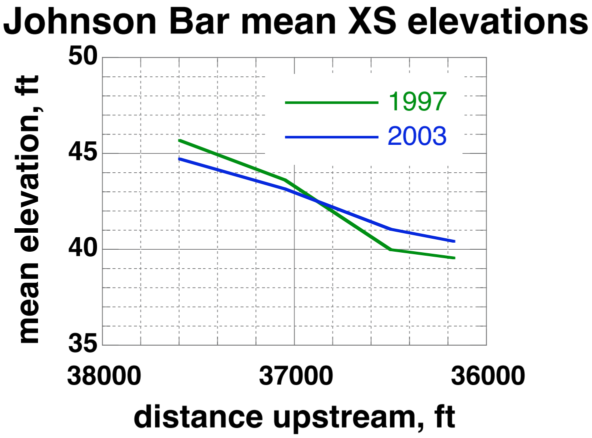


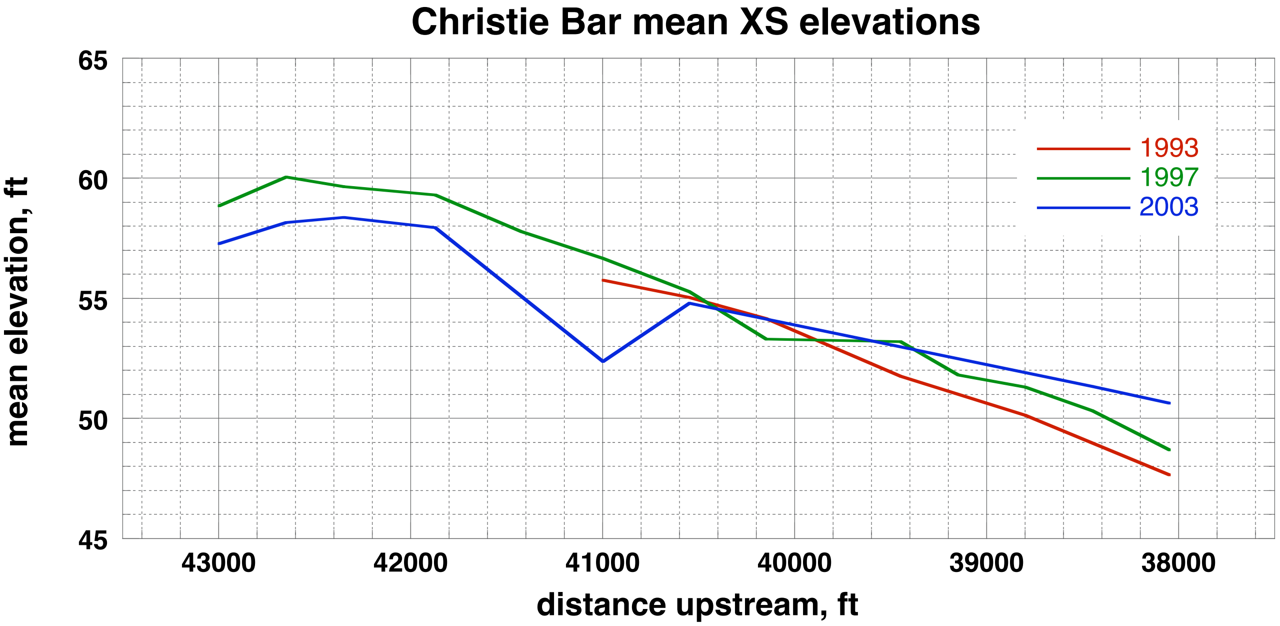
Emmerson Bar mean XS elevations

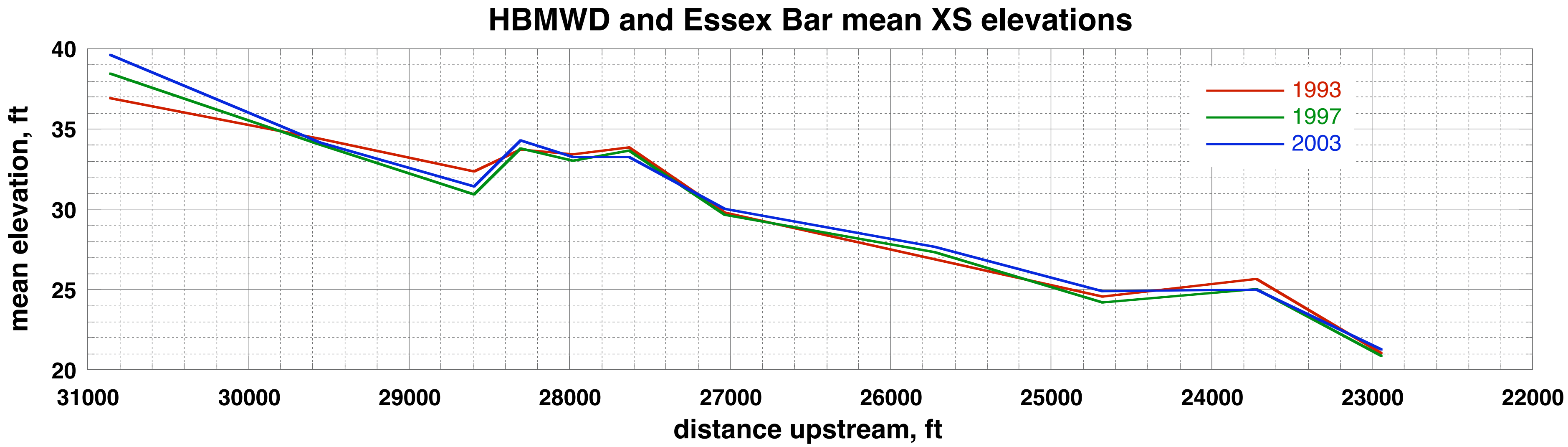


Blue Lake Bar mean XS elevations

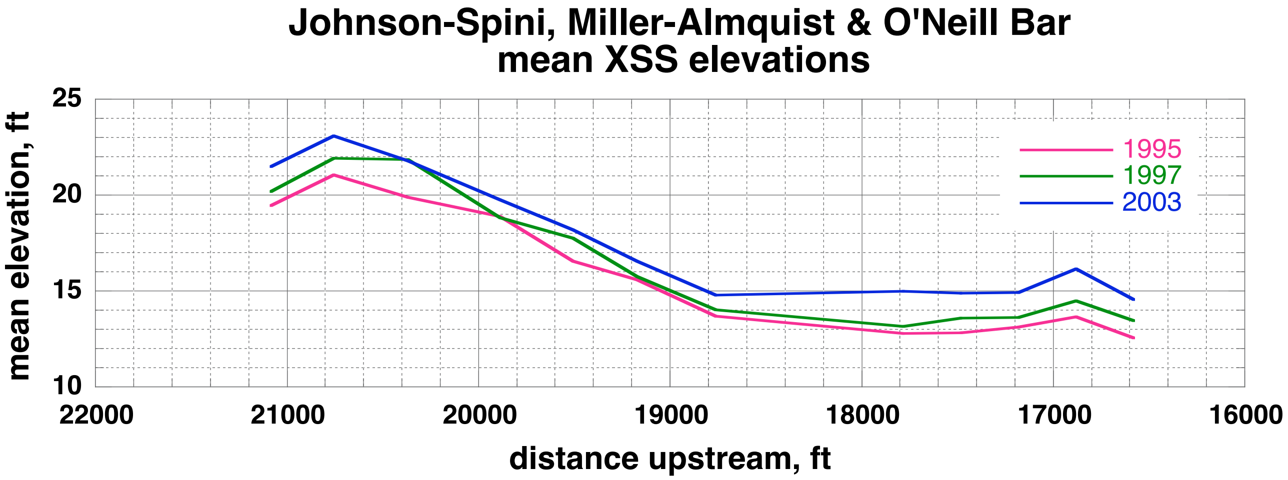



Johnson Bar mean XS elevations
mean elevation, ft
50
45
40
35
38000
37000
36000
distance upstream, ft
1997
2003


Christie Bar mean XS elevations
mean elevation, ft
65
60
55
50
45
43000
42000
41000
40000
39000
38000
distance upstream, ft
1993
1997
2003



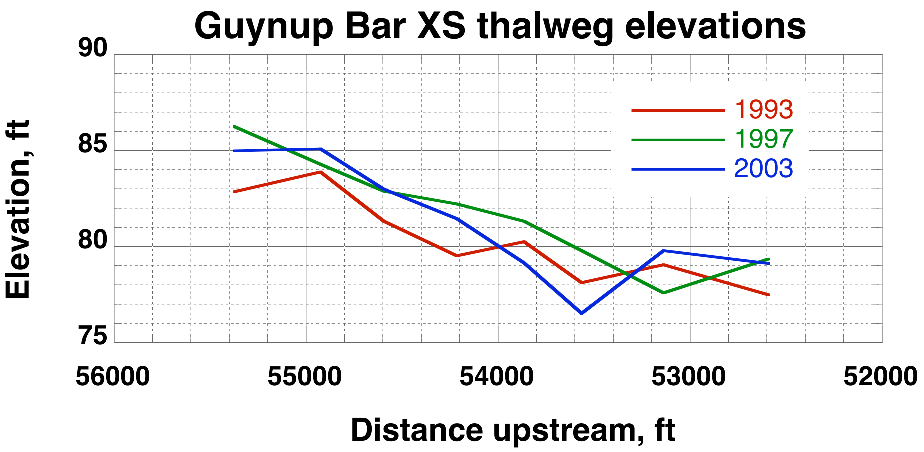
HBMWD and Essex Bar mean XS elevations

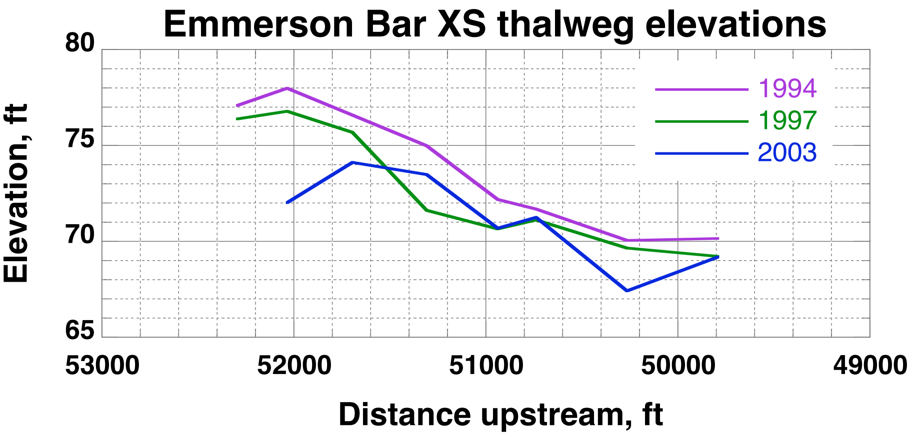


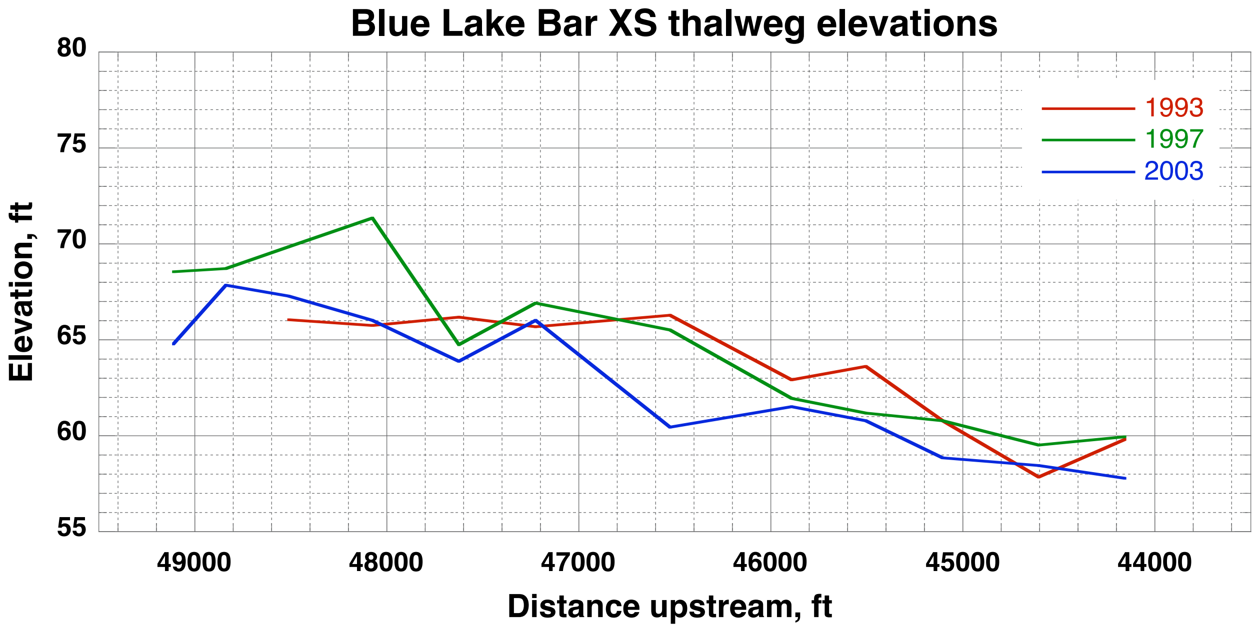
Johnson-Spini, Miller-Almquist & O'Neill Bar
mean XSS elevations

Appendix C

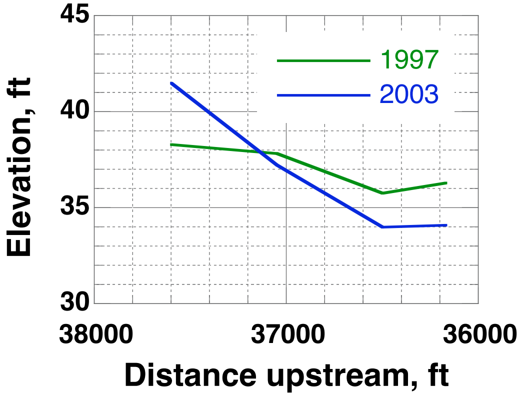
Thalweg profiles, by bars
1993, 1997, 2003


Guynup Bar XS thalweg elevations
Elevation, ft
90
85
80
75
56000
55000
54000
53000
52000
Distance upstream, ft
1993
1997
2003


Emmerson Bar XS thalweg elevations
Elevation, ft
80
75
70
65
53000
52000
51000
50000
49000
Distance upstream, ft
1994
1997
2003

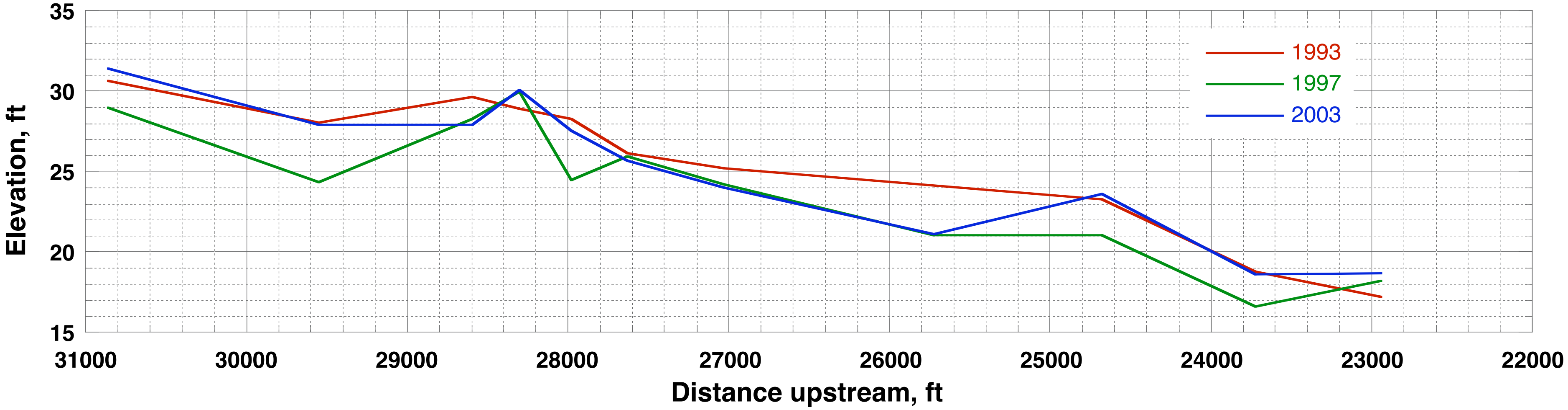

Blue Lake Bar XS thalweg elevations
Elevation, ft
80
75
70
65
60
55
49000
48000
47000
46000
45000
44000
Distance upstream, ft
1993
1997
2003

Christie Bar XS thalweg elevations

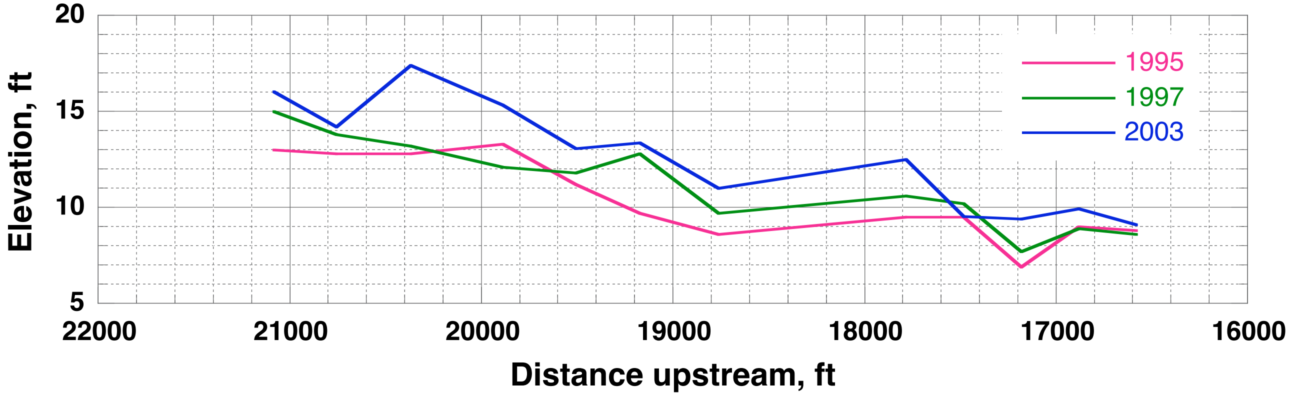


Johnson Bar XS thalweg elevations

HBMWD and Essex Bar XS thalweg elevations

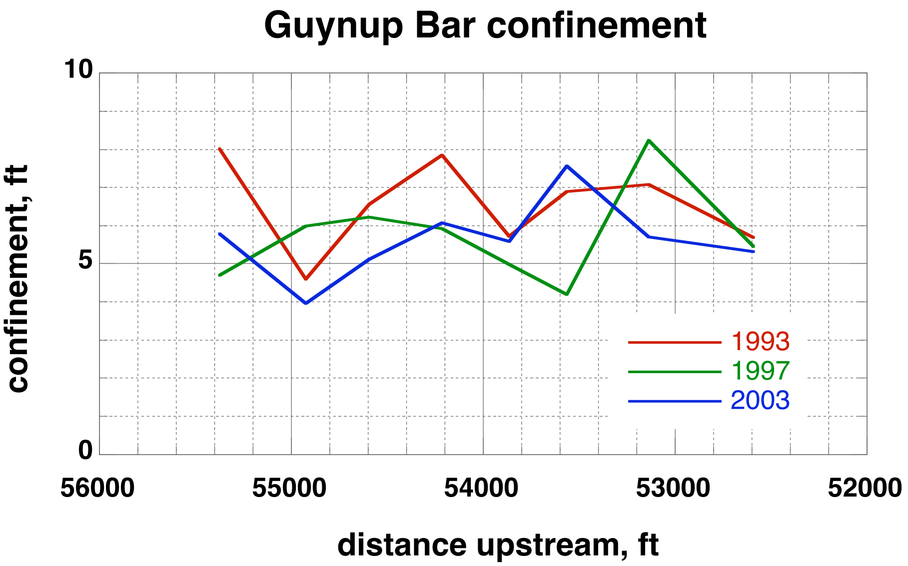


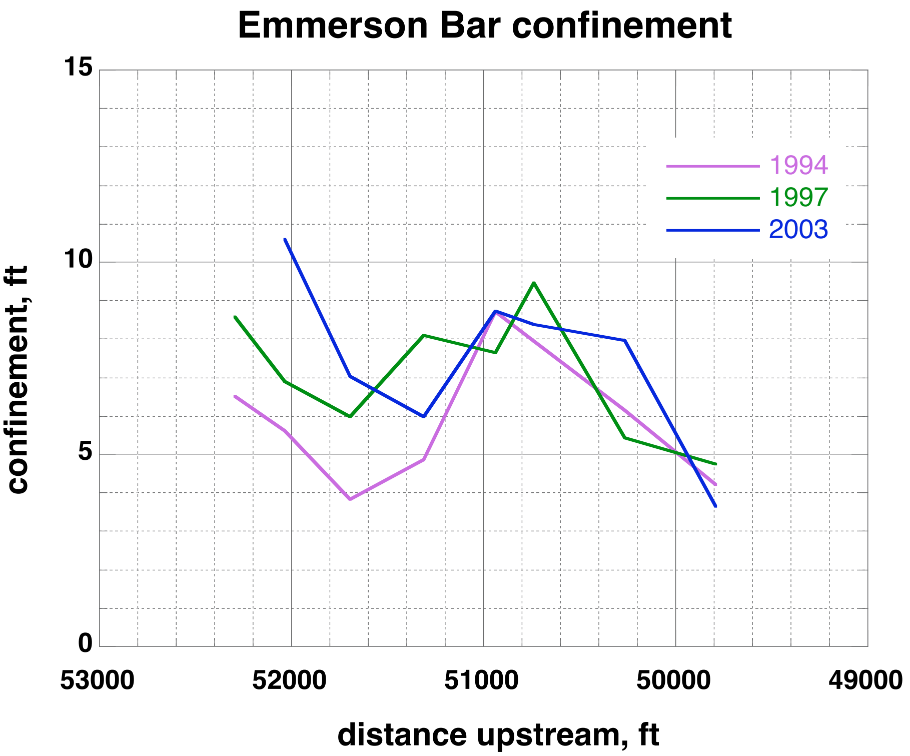
Johnson-Spini, Miller-Almquist & O'Neill Bar XSS thalweg elevations

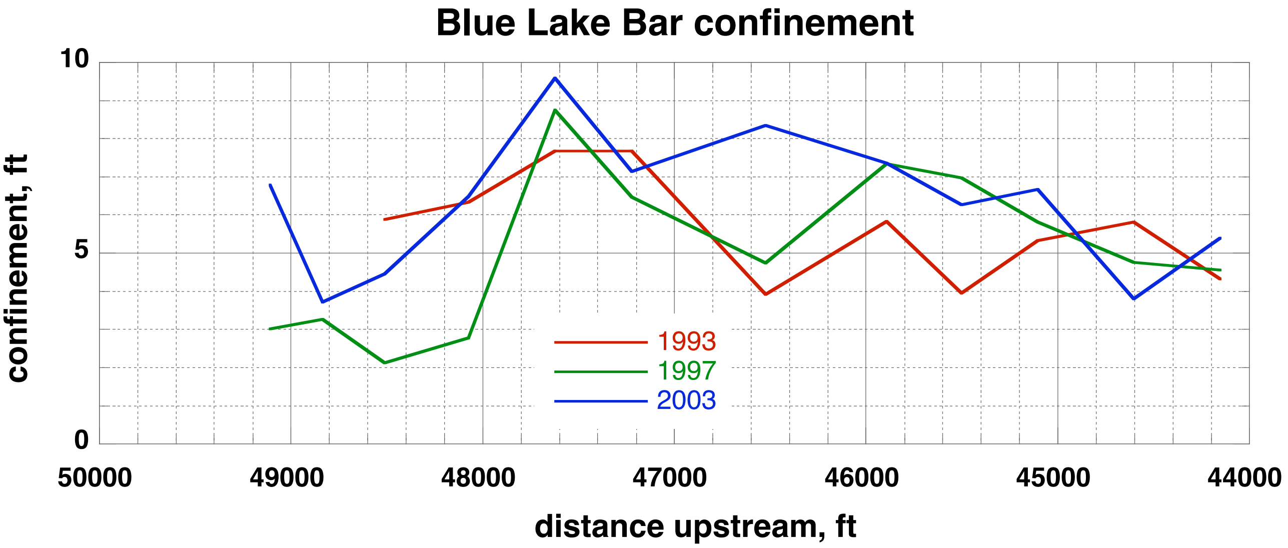


Appendix D

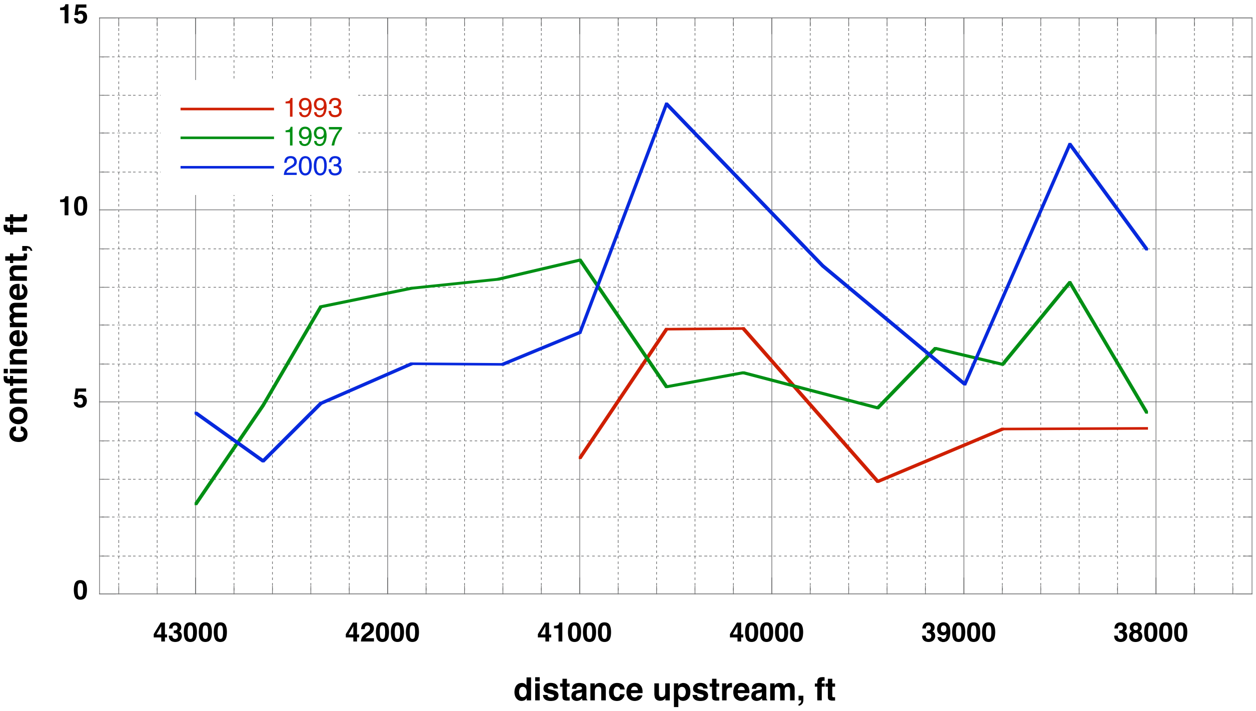
Confinement vs streamwise distance, by bars
1993, 1997, 2003


Guynup Bar confinement

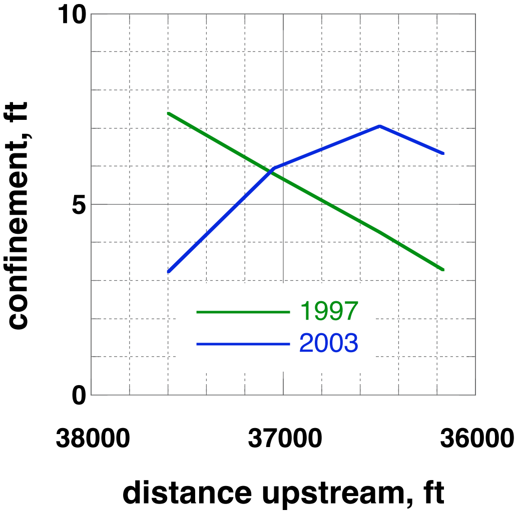

Emmerson Bar confinement

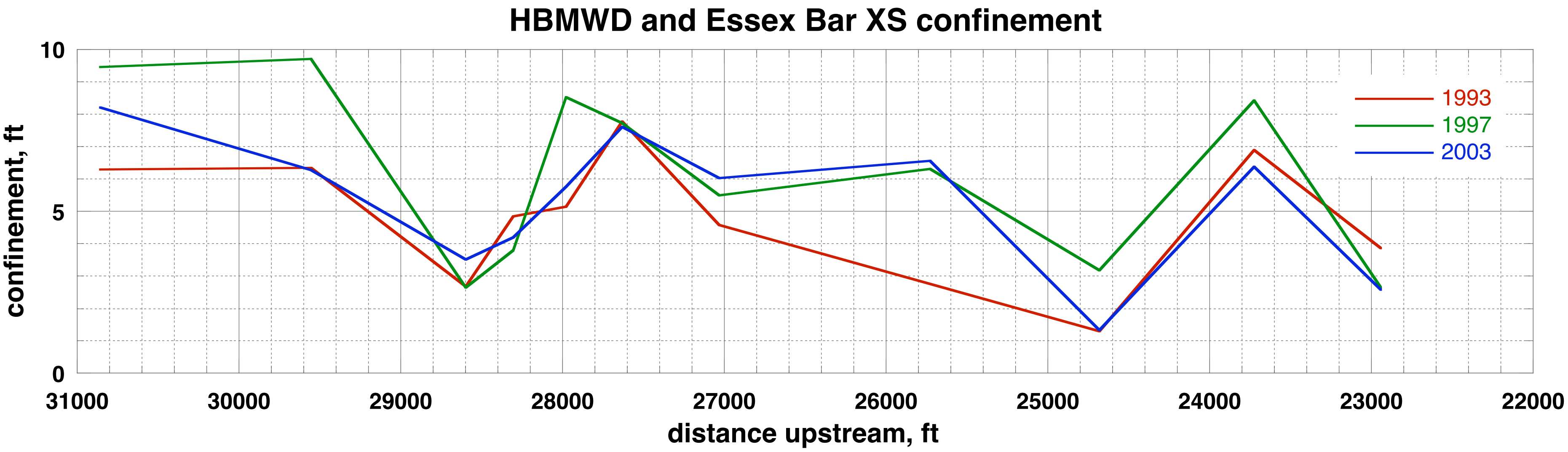

Blue Lake Bar confinement

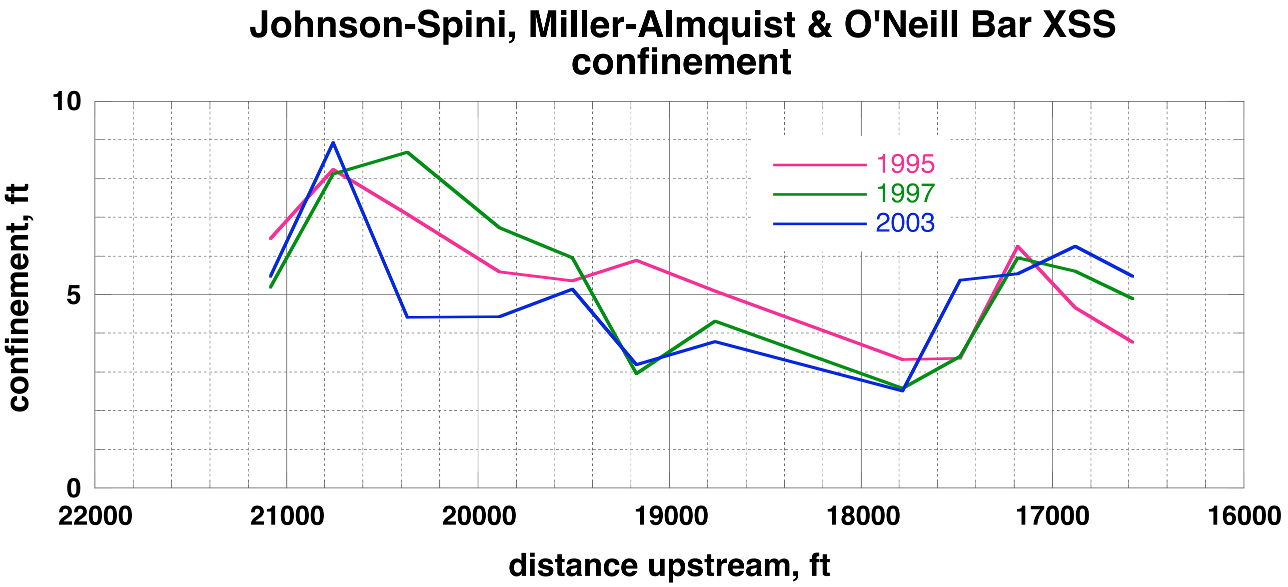
Christie Bar confinement



Johnson Bar XS confinement

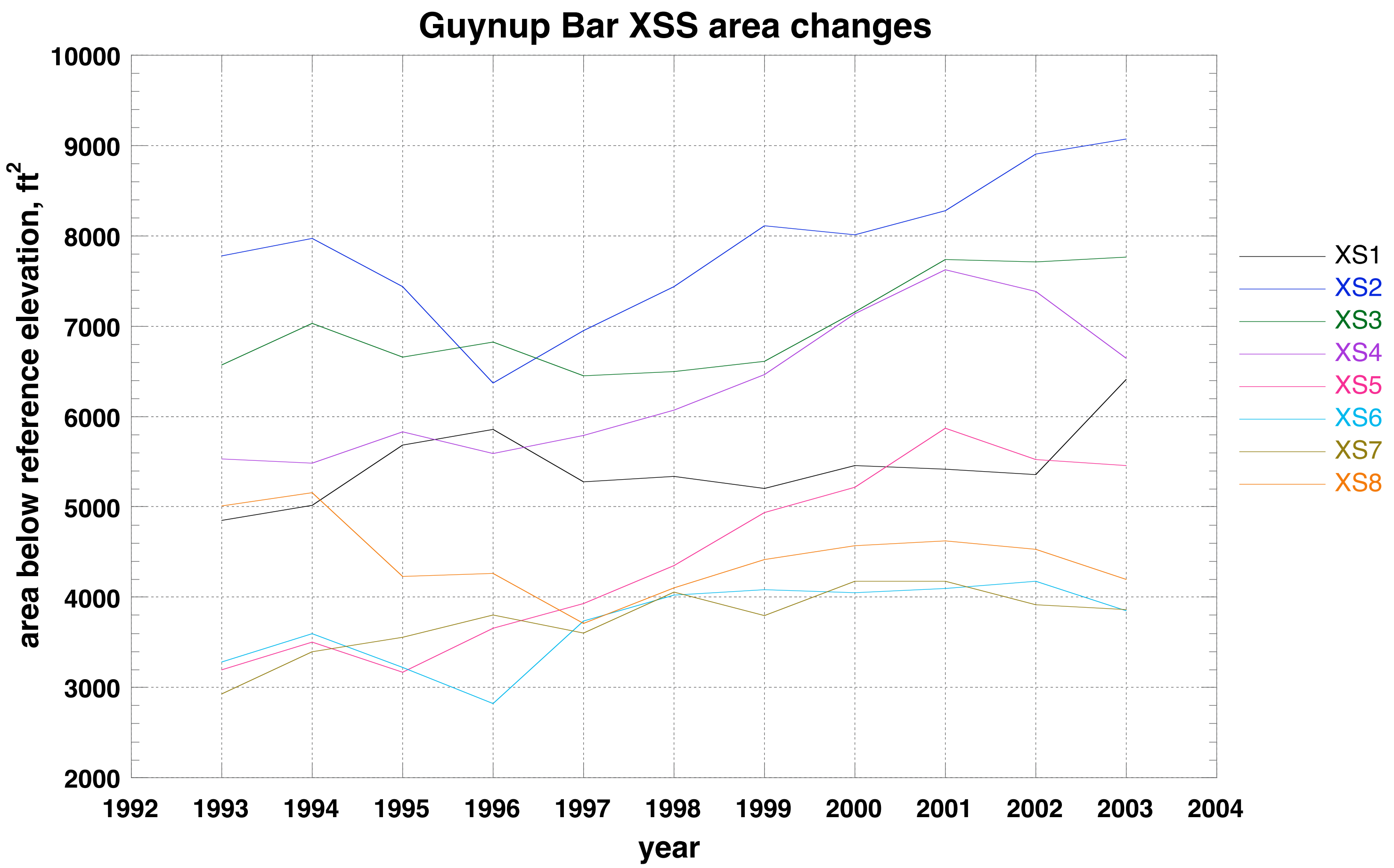


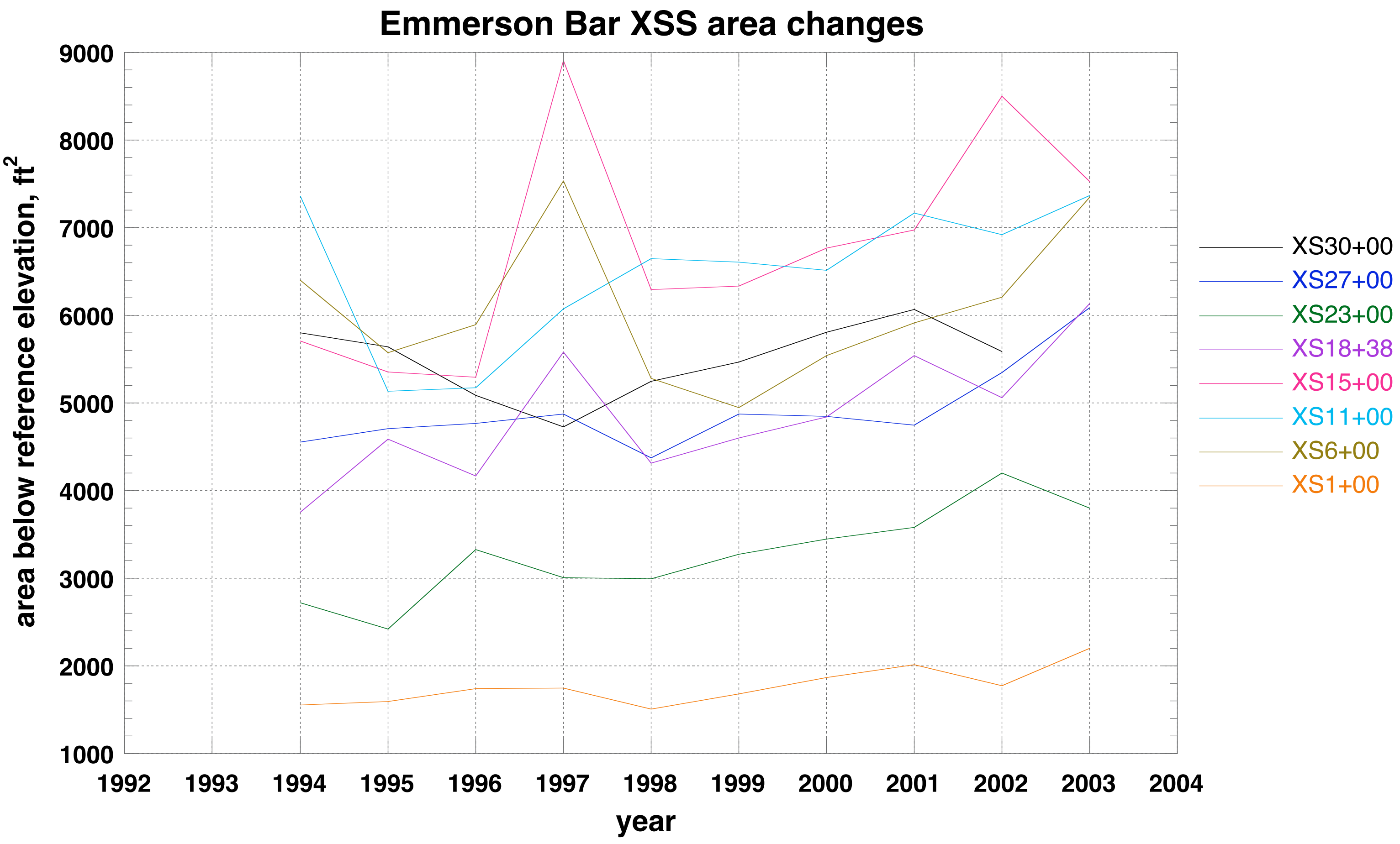

HBMWD and Essex Bar XS confinement

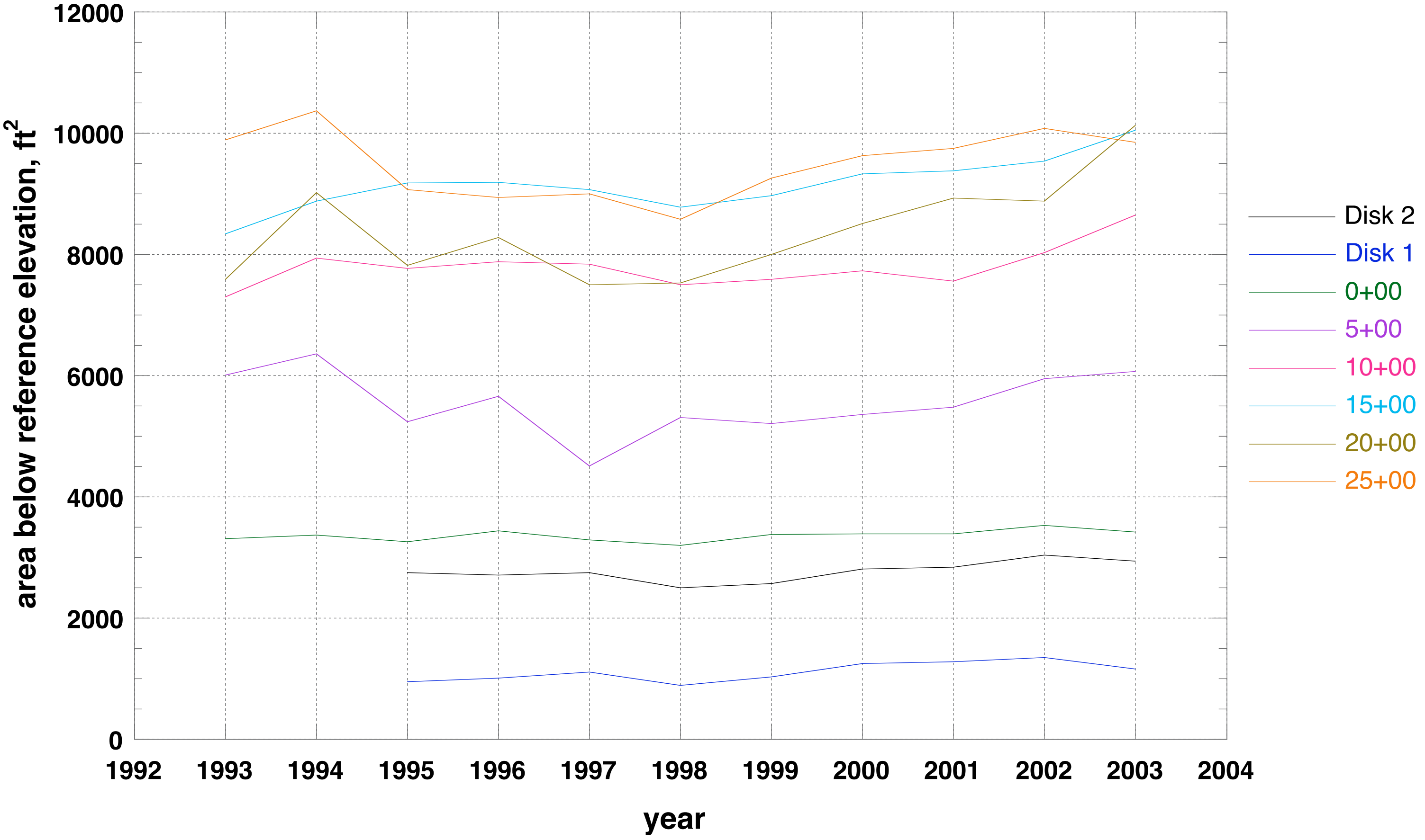

Johnson-Spini, Miller-Almquist & O'Neill Bar XSS confinement

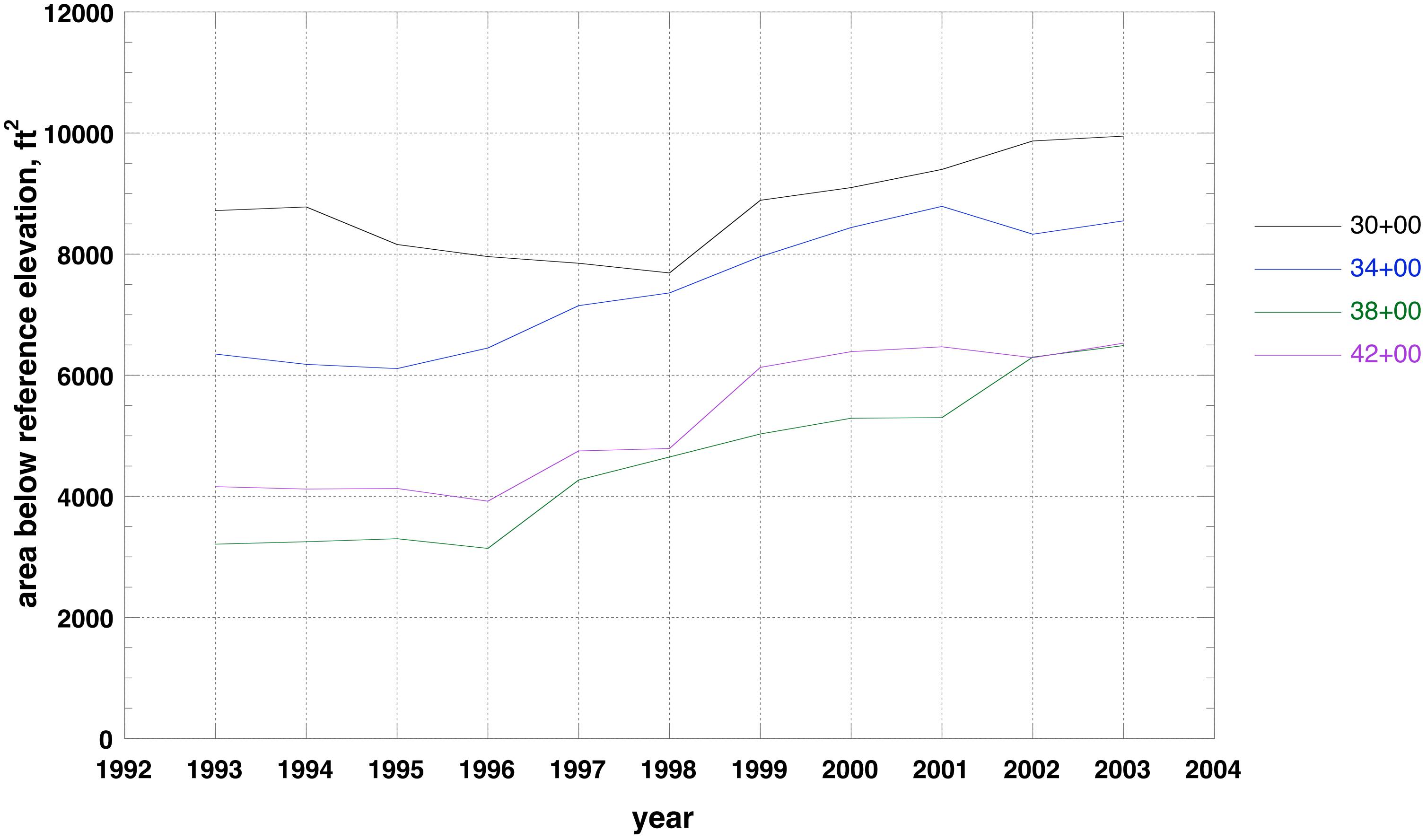
Appendix E

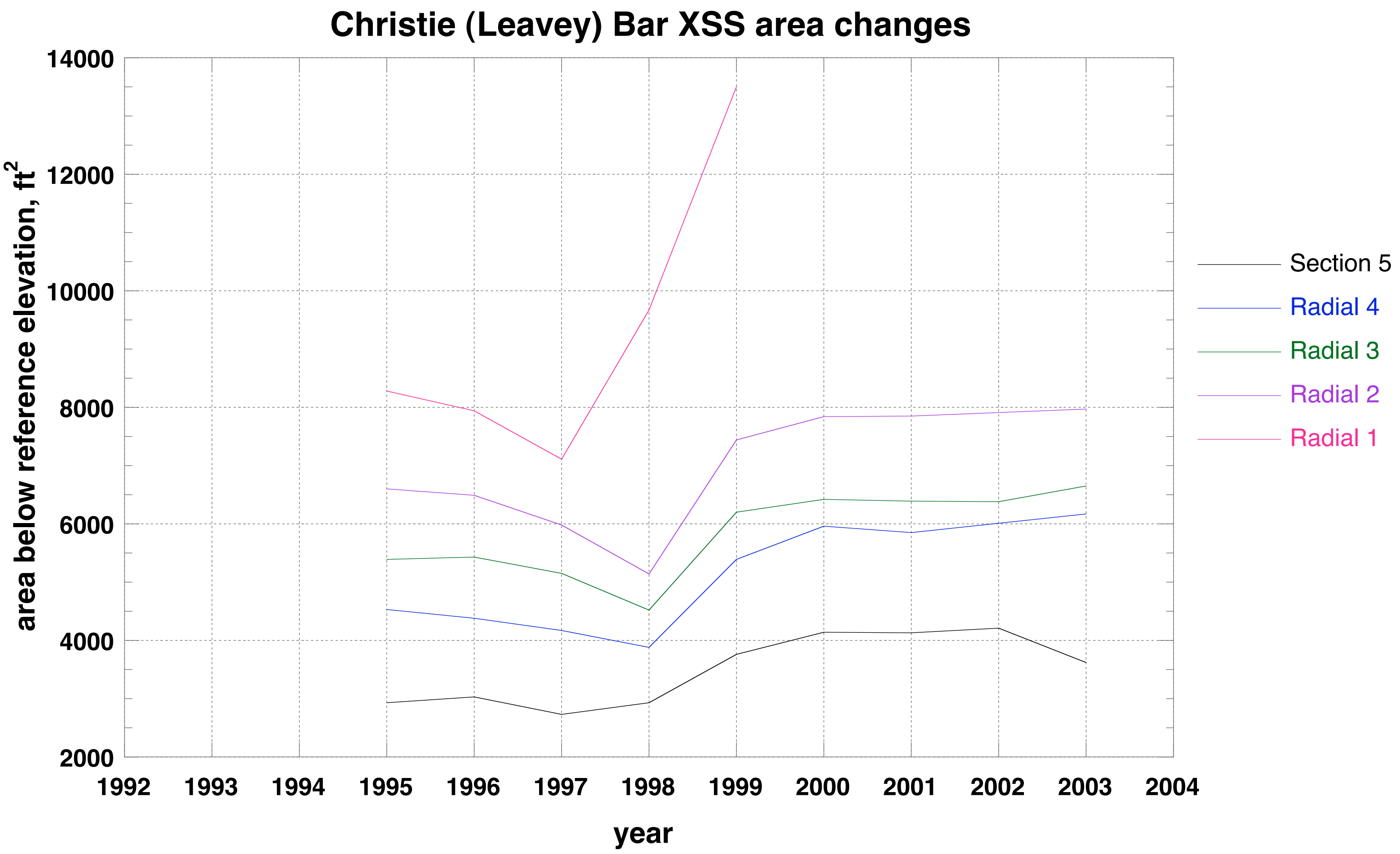
XS area changes with time, by bars

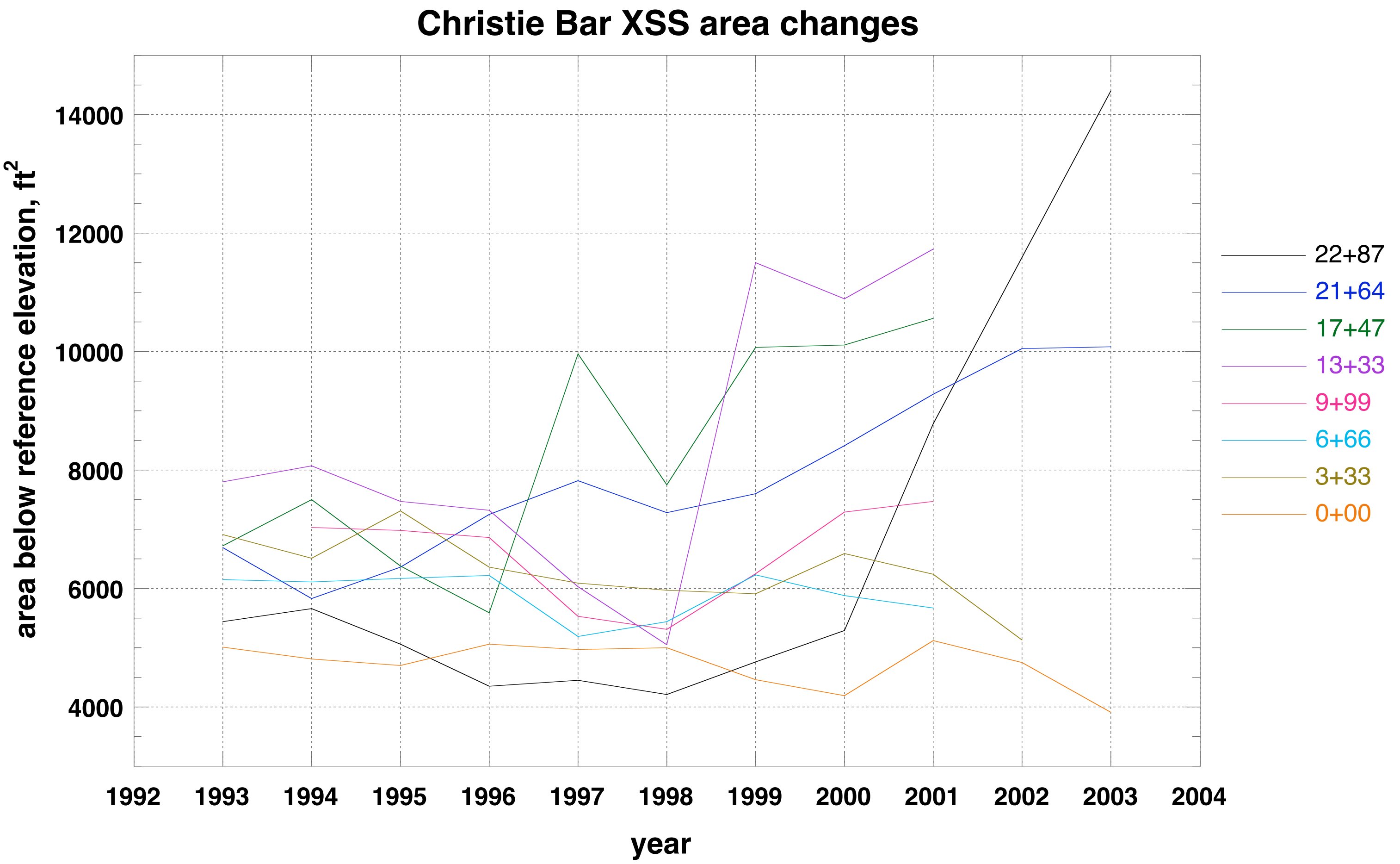

Guynup Bar XSS area changes
area below reference elevation, ft^2
10000
9000
8000
7000
6000
5000
4000
3000
2000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
XS1
XS2
XS3
XS4
XS5
XS6
XS7
XS8

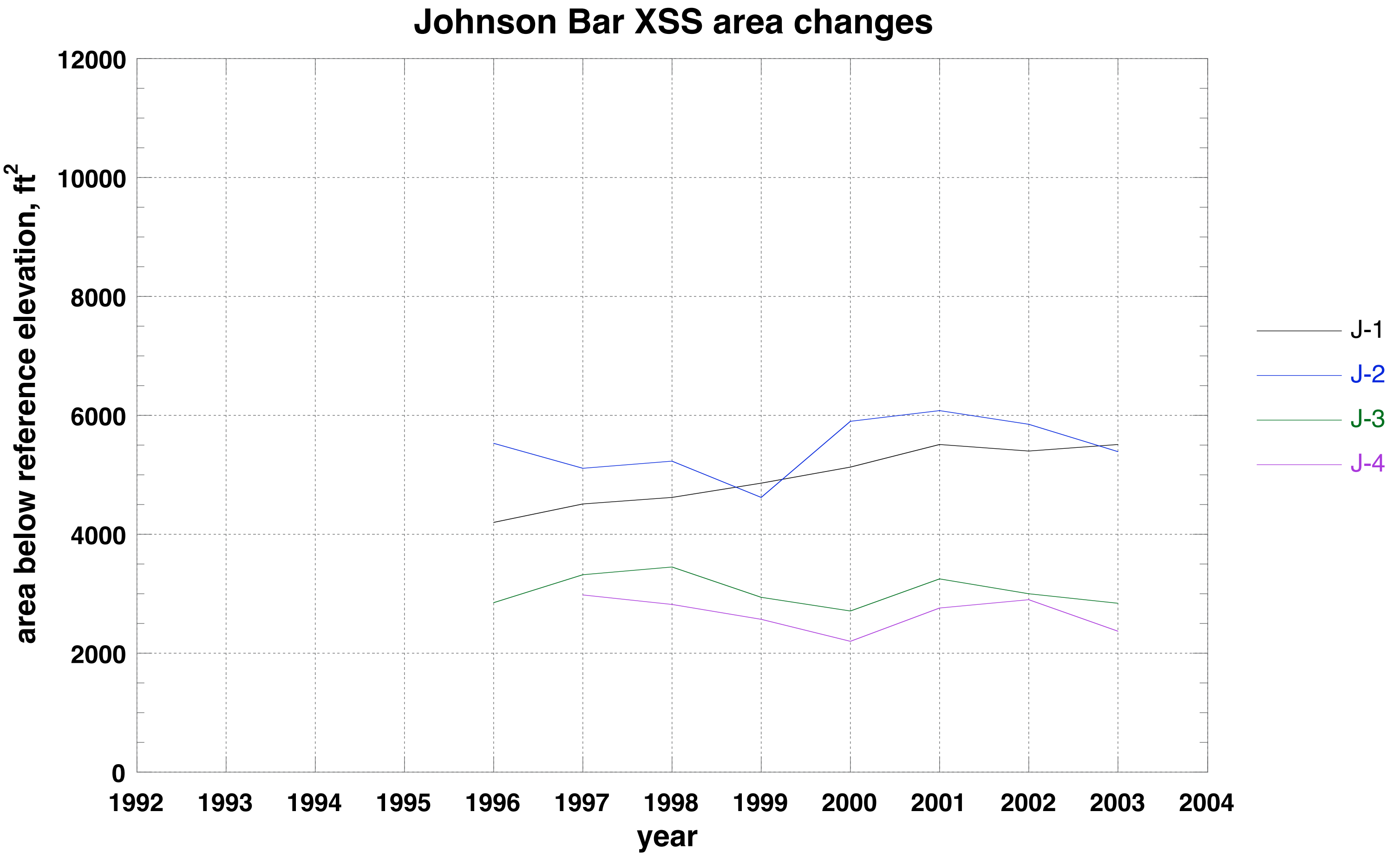

Emmerson Bar XSS area changes
area below reference elevation, ft^2
9000
8000
7000
6000
5000
4000
3000
2000
1000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
XS30+00
XS27+00
XS23+00
XS18+38
XS15+00
XS11+00
XS6+00
XS1+00

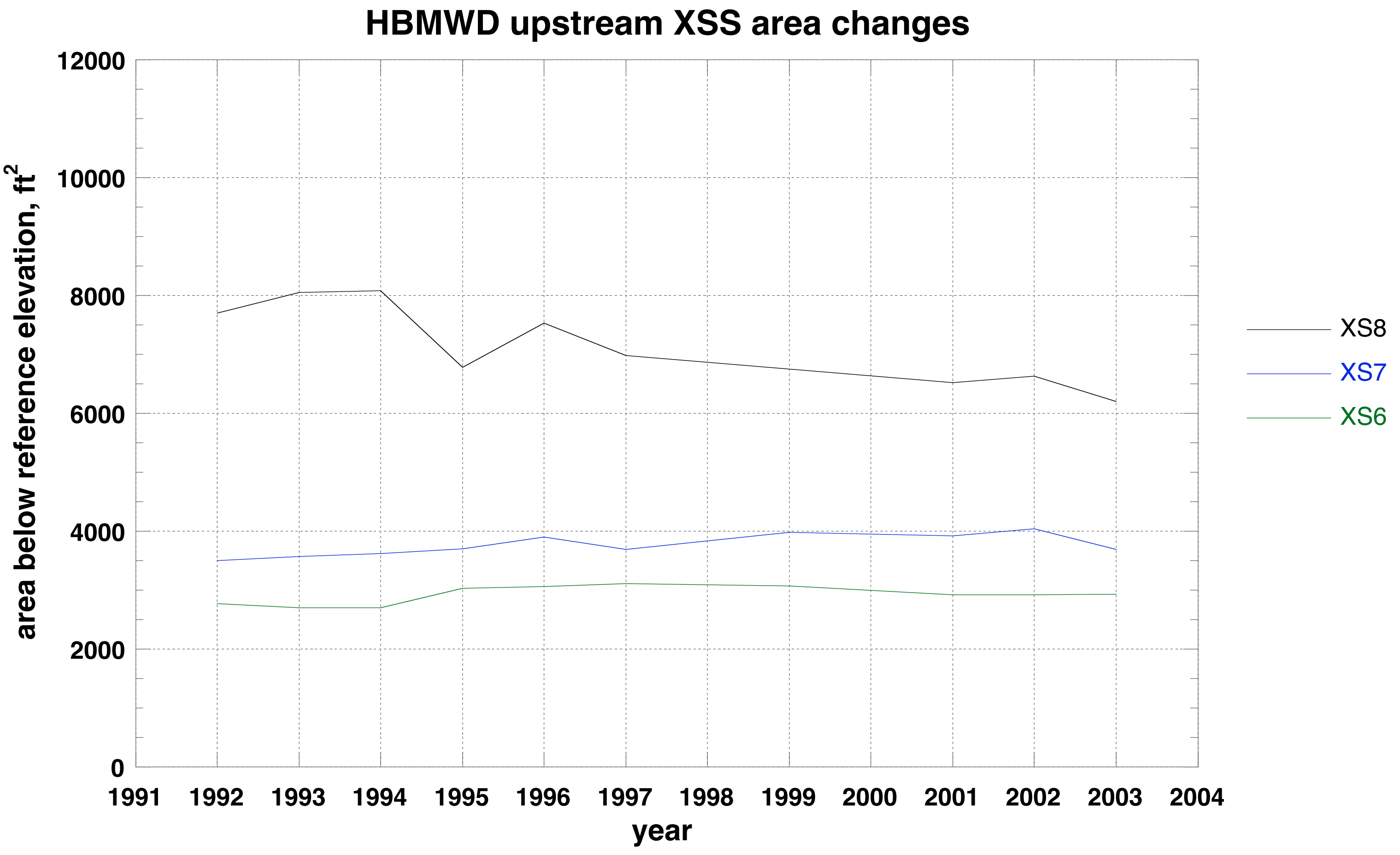

Blue Lake Bar XSS area changes

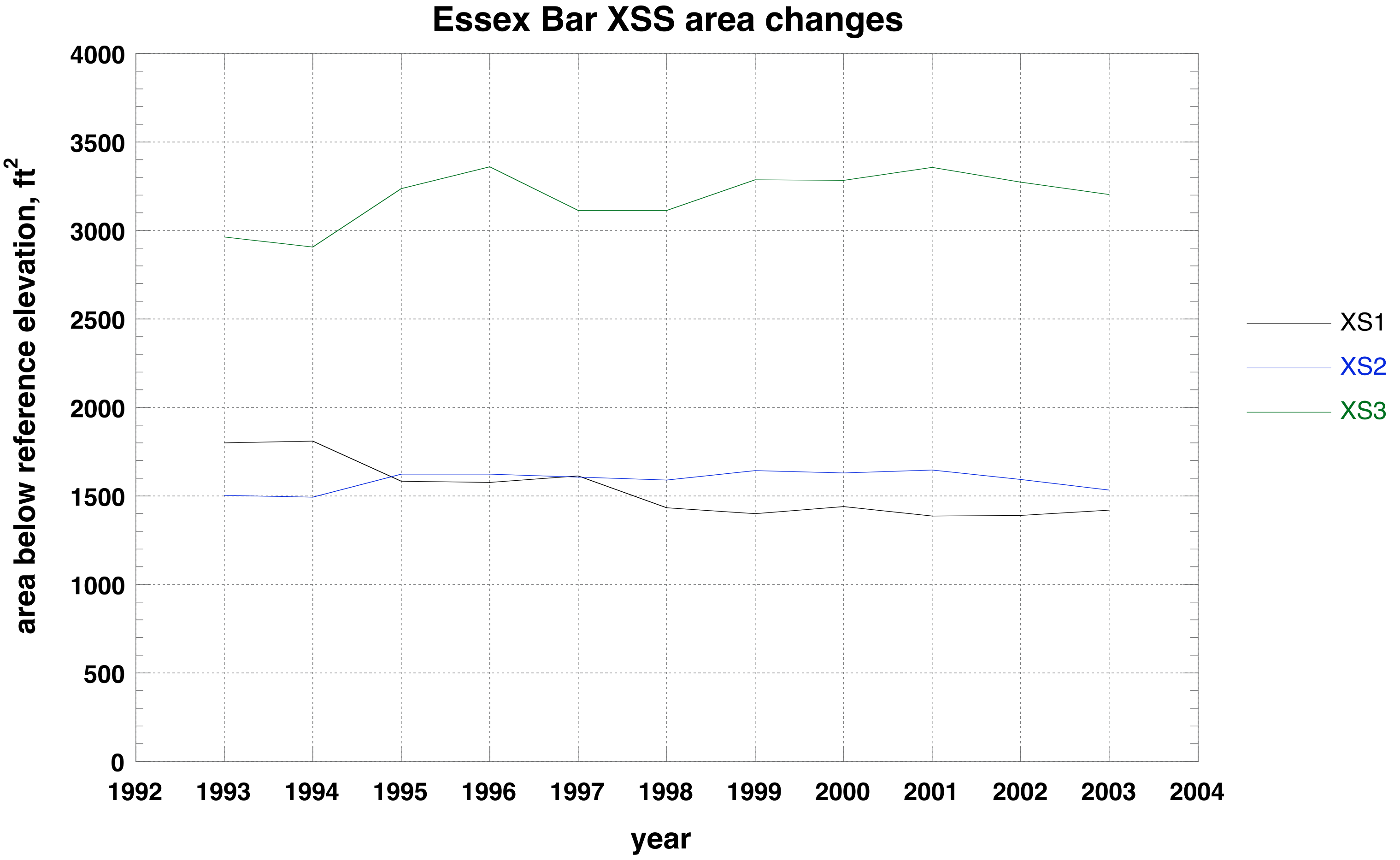

Blue Lake Bar XSS area changes

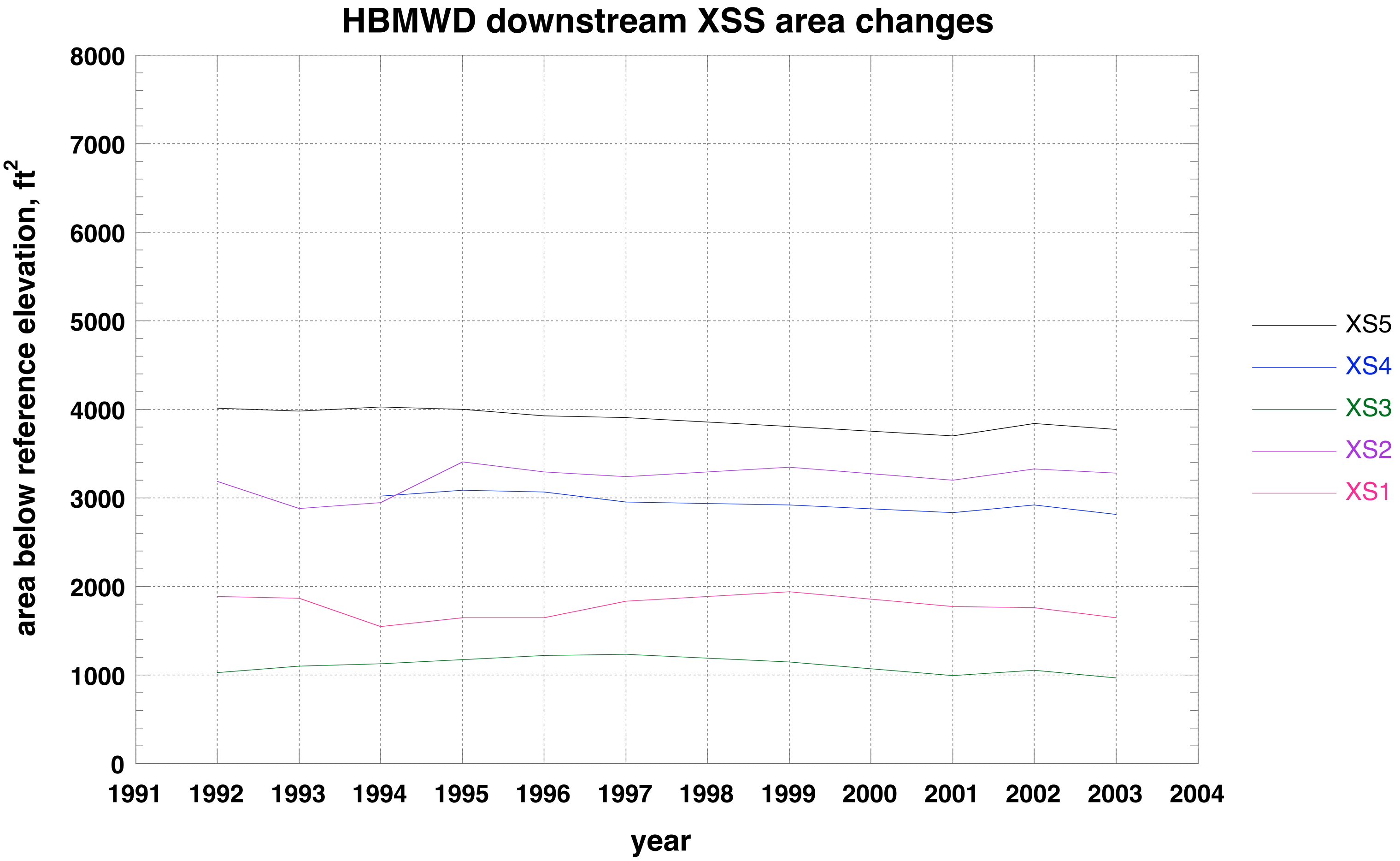

Christie (Leavey) Bar XSS area changes
area below reference elevation, ft^2
14000
12000
10000
8000
6000
4000
2000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
Section 5
Radial 4
Radial 3
Radial 2
Radial 1

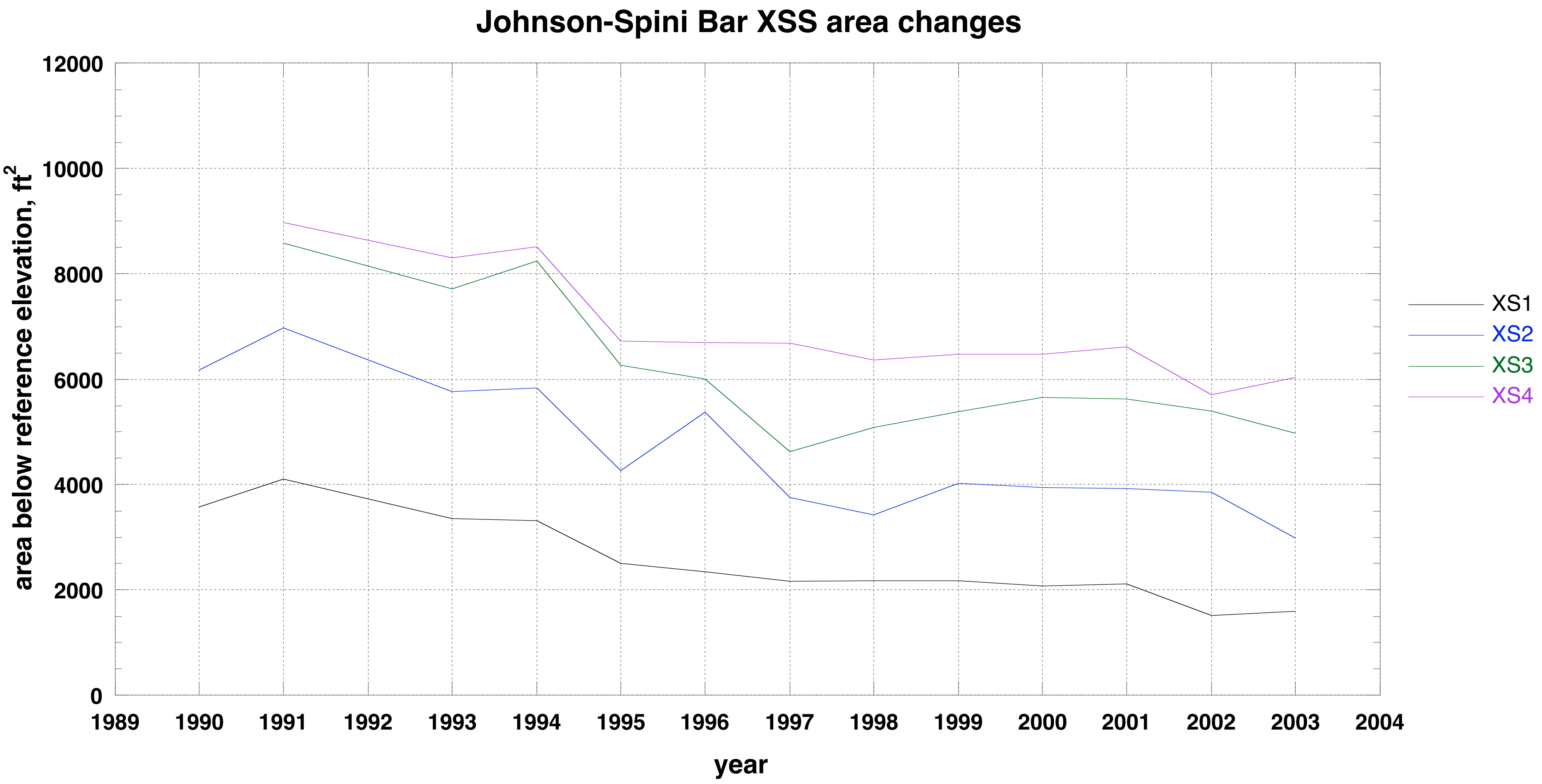

Christie Bar XSS area changes
area below reference elevation, ft^2
14000
12000
10000
8000
6000
4000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
22+87
21+64
17+47
13+33
9+99
6+66
3+33
0+00

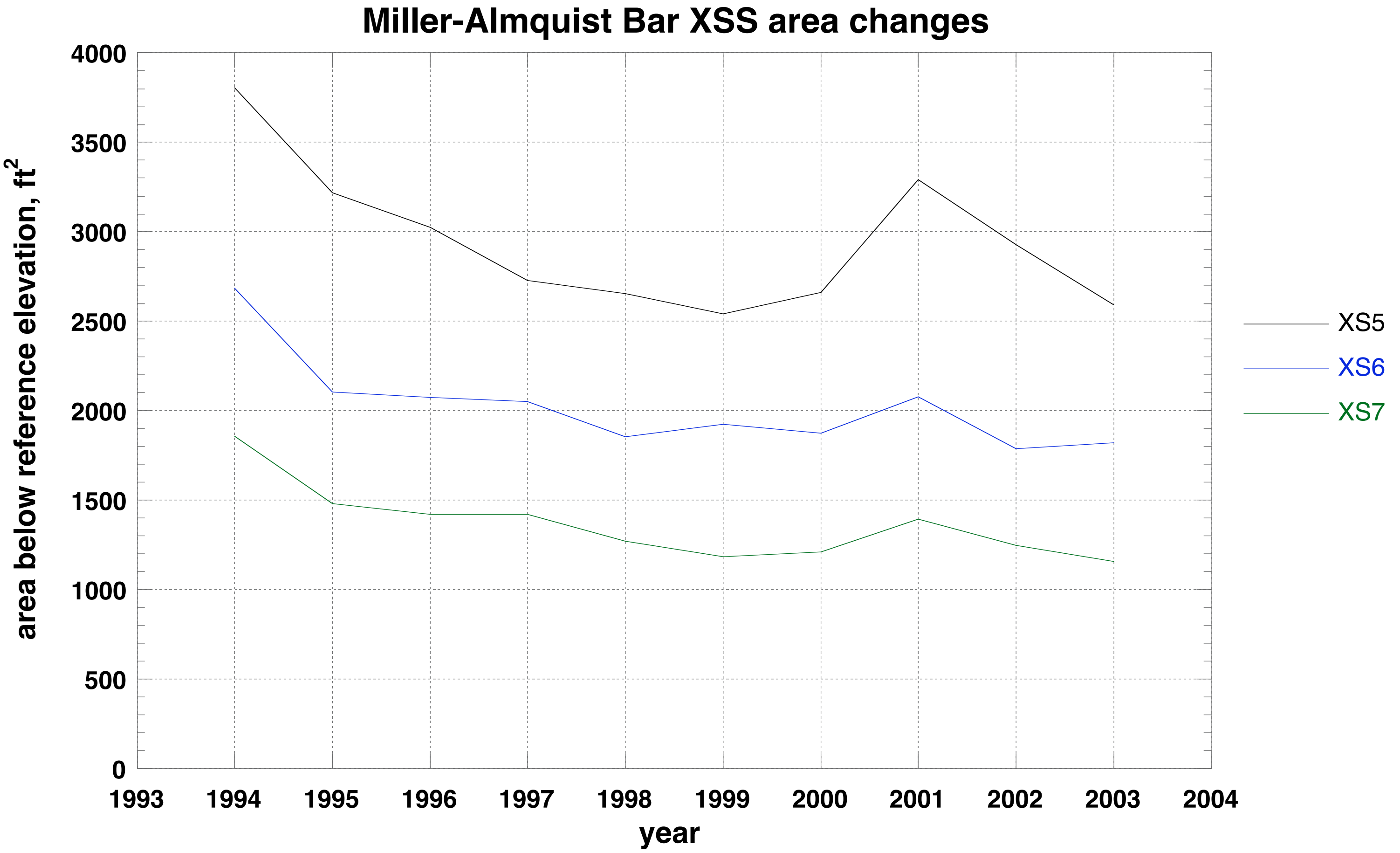

Johnson Bar XSS area changes
area below reference elevation, ft^2
0
2000
4000
6000
8000
10000
12000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
J-1
J-2
J-3
J-4

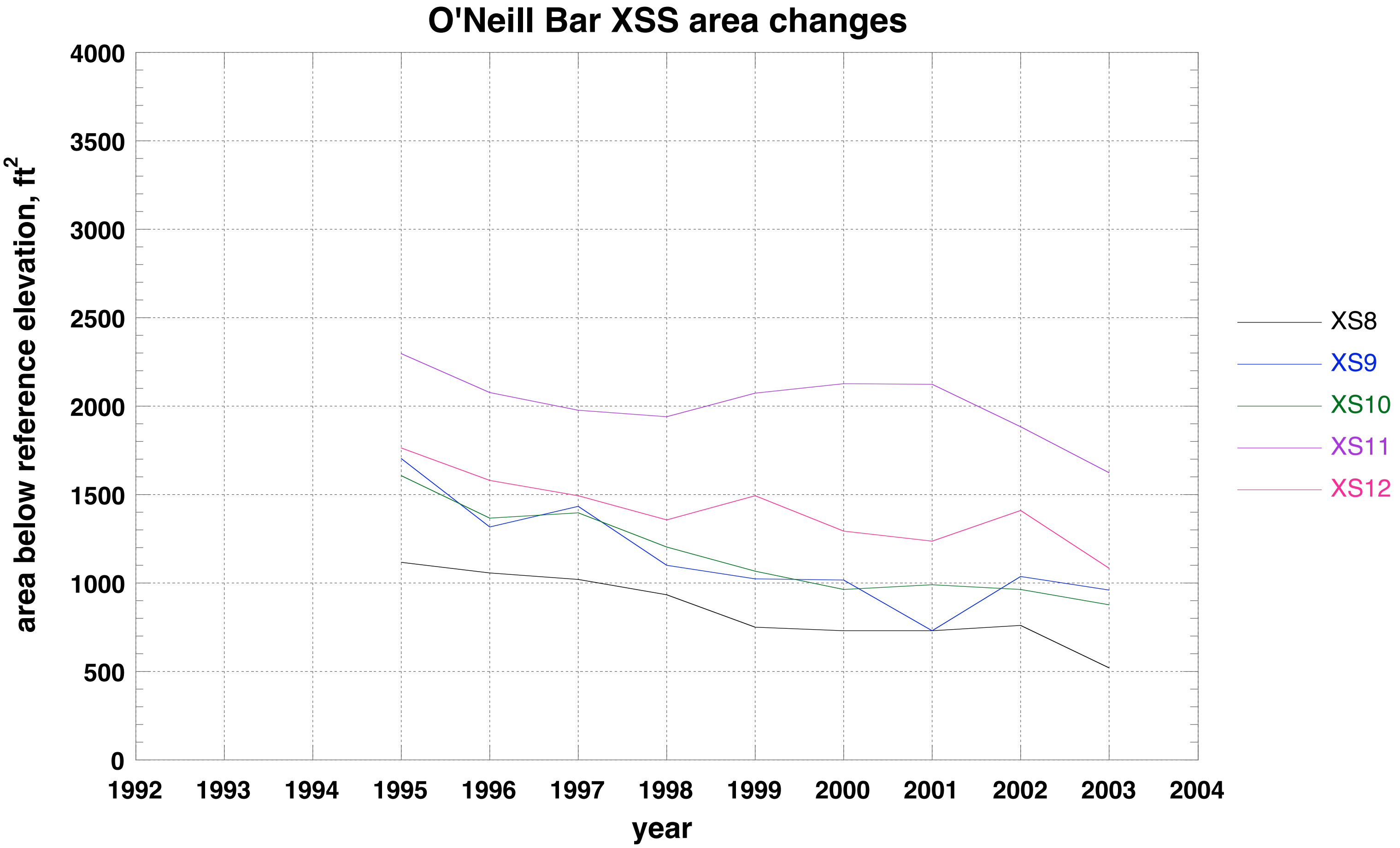

HBMWD upstream XSS area changes
area below reference elevation, ft^2
0
2000
4000
6000
8000
10000
12000
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
XS8
XS7
XS6


Essex Bar XSS area changes
area below reference elevation, ft²
year
4000
3500
3000
2500
2000
1500
1000
500
0
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
XS1
XS2
XS3


HBMWD downstream XSS area changes
area below reference elevation, ft²
year
8000
7000
6000
5000
4000
3000
2000
1000
0
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
XS5
XS4
XS3
XS2
XS1

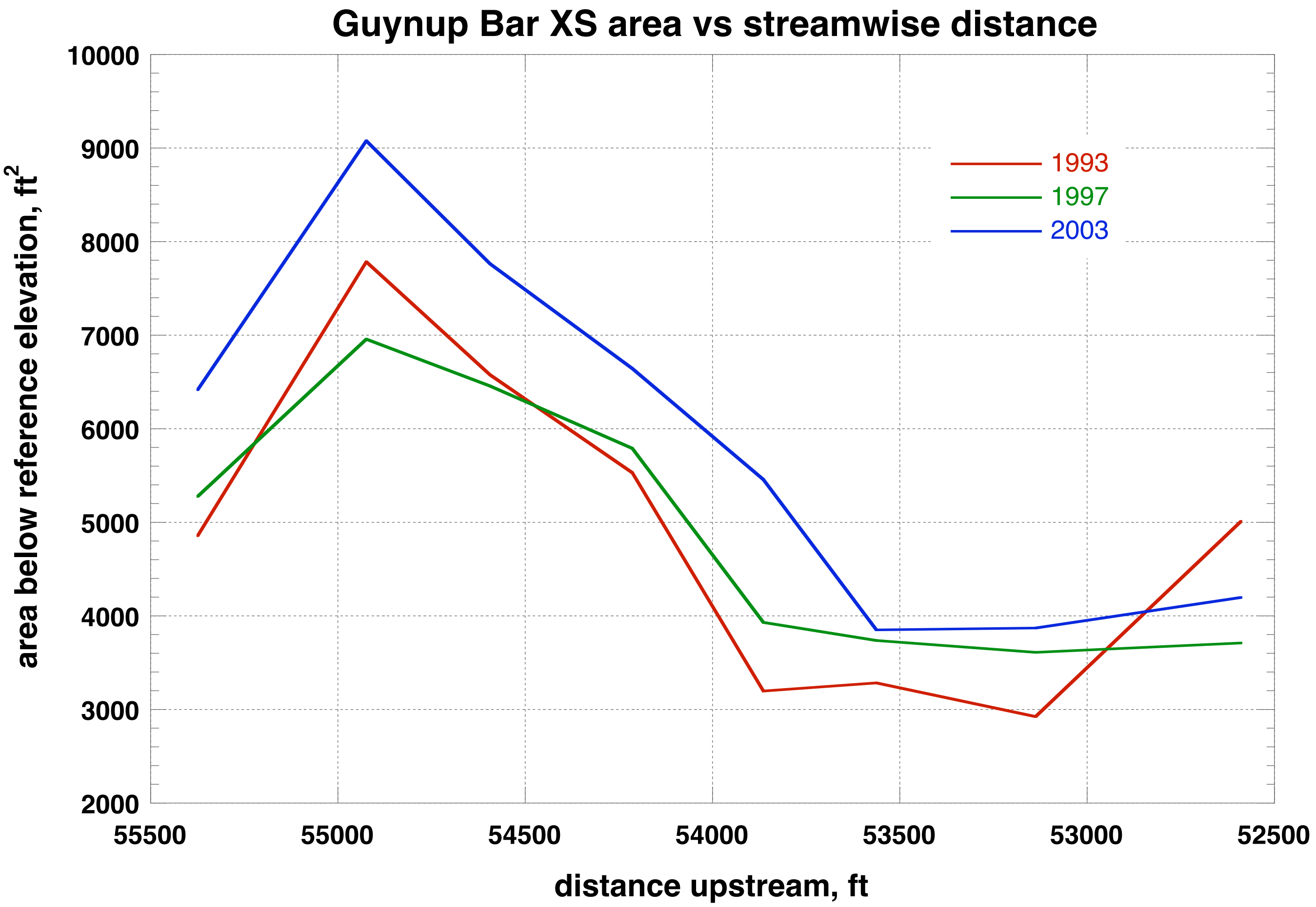

Johnson-Spini Bar XSS area changes
area below reference elevation, ft^2
12000
10000
8000
6000
4000
2000
0
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
XS1
XS2
XS3
XS4

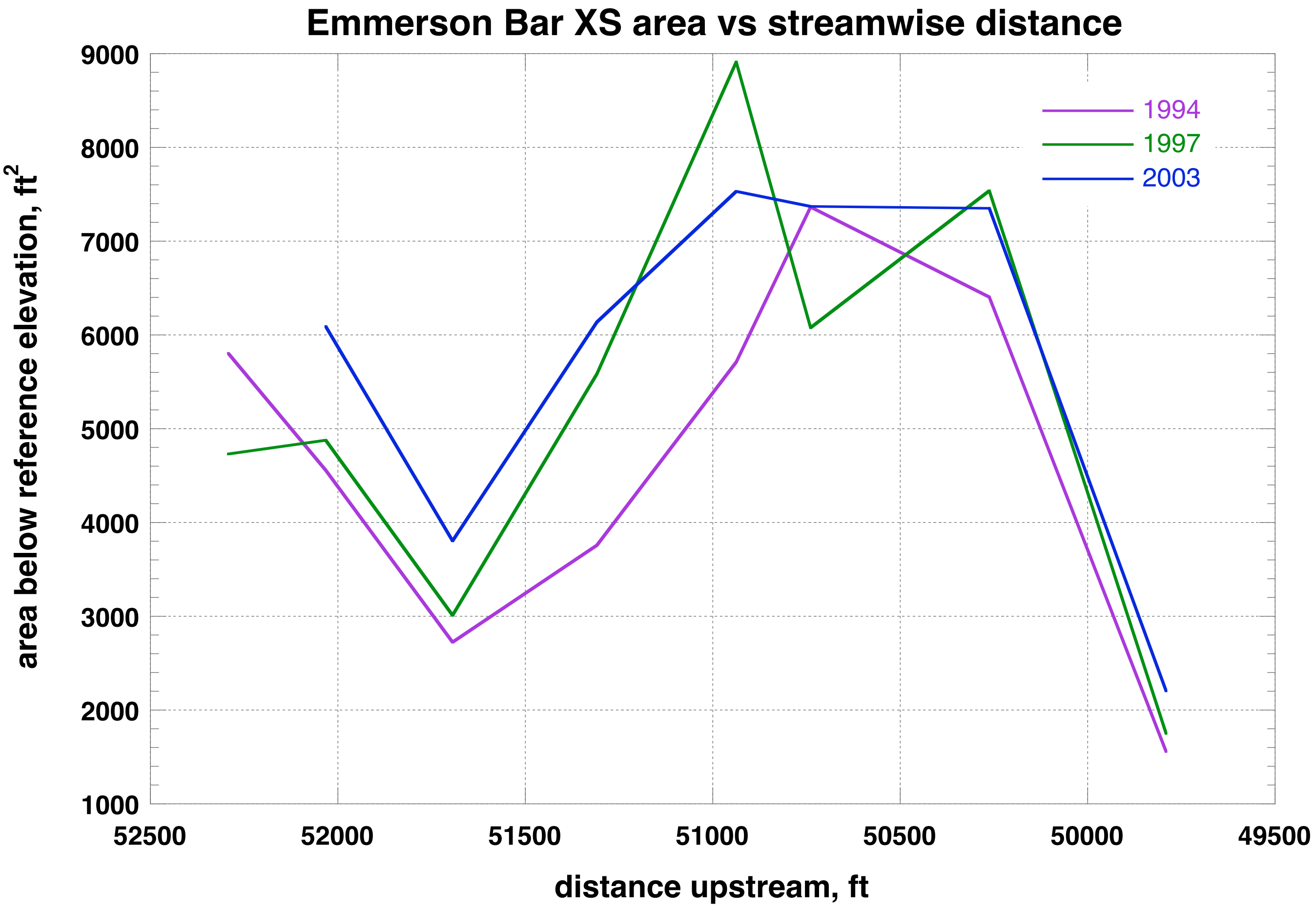

Miller-Almquist Bar XSS area changes
area below reference elevation, ft^2
year
0
500
1000
1500
2000
2500
3000
3500
4000
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
XS5
XS6
XS7

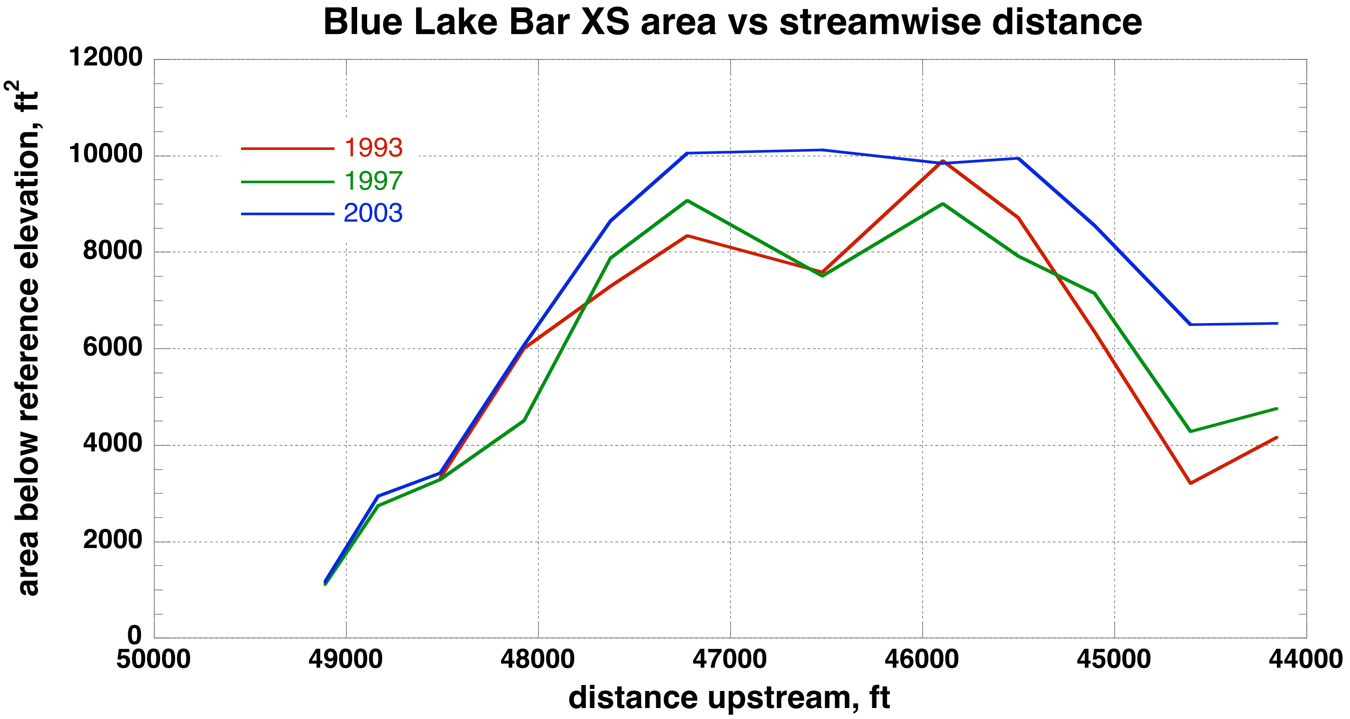

O'Neill Bar XSS area changes
area below reference elevation, ft^2
year
0
500
1000
1500
2000
2500
3000
3500
4000
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
XS8
XS9
XS10
XS11
XS12

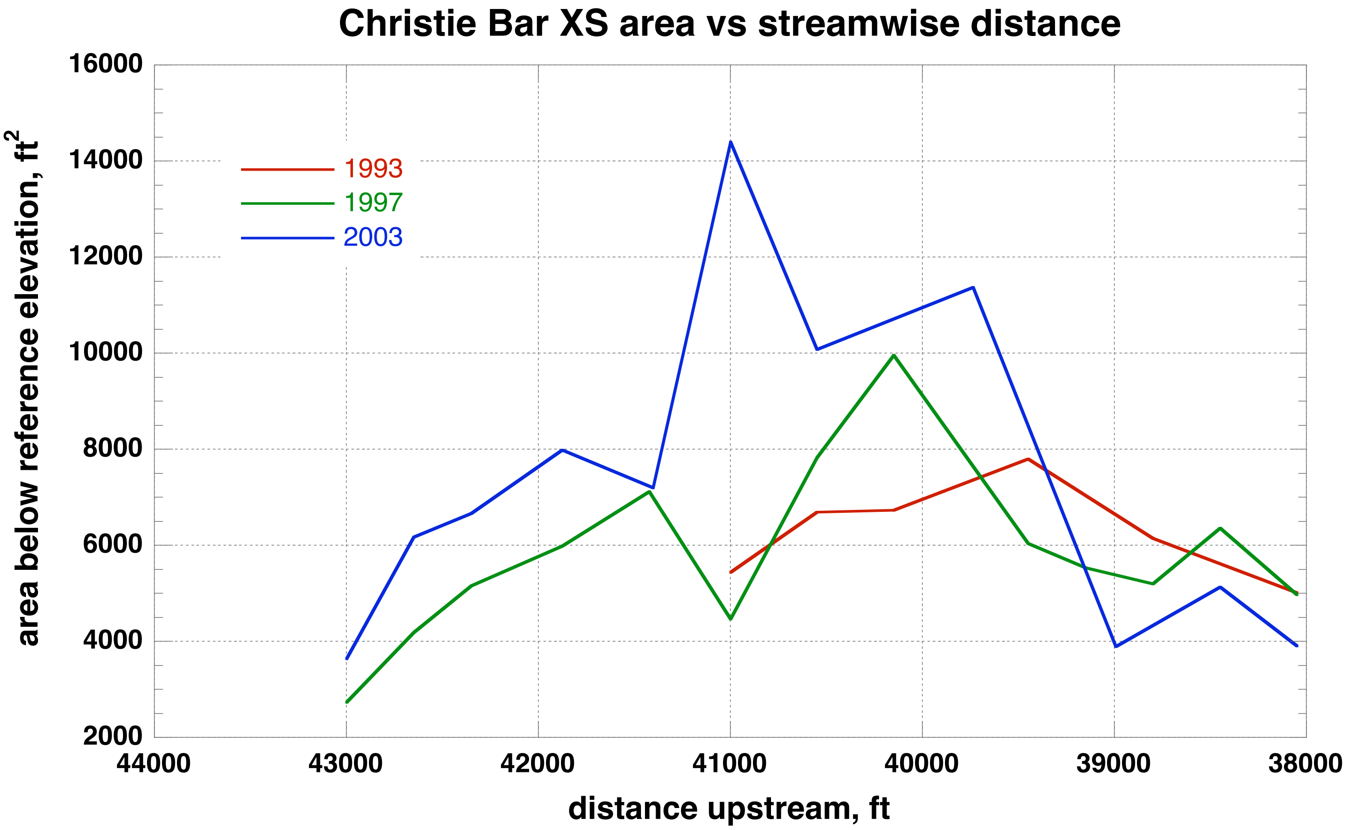
Appendix F

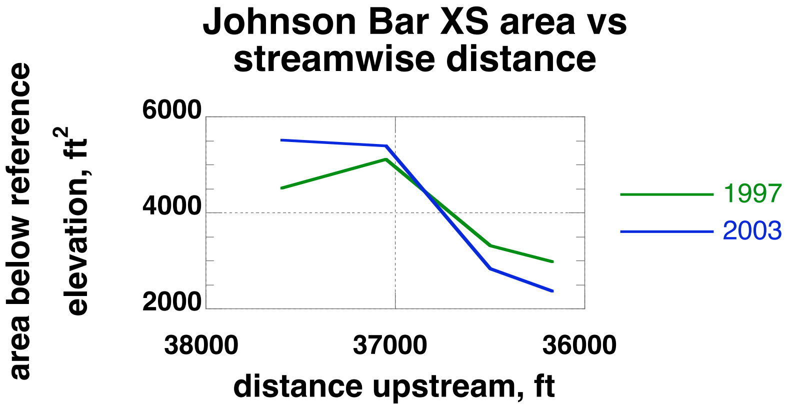
XS area vs streamwise distance, by bars
1993, 1997, 2003

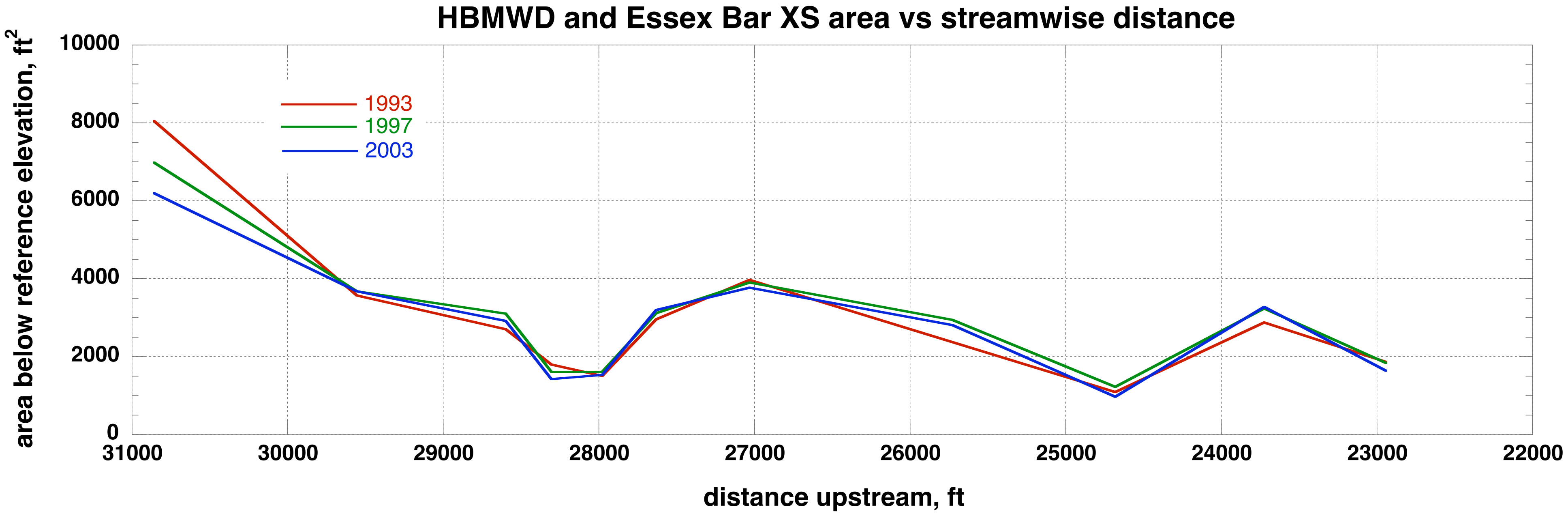

Guynup Bar XS area vs streamwise distance
area below reference elevation, ft^2
10000
9000
8000
7000
6000
5000
4000
3000
2000
55500
55000
54500
54000
53500
53000
52500
distance upstream, ft
1993
1997
2003

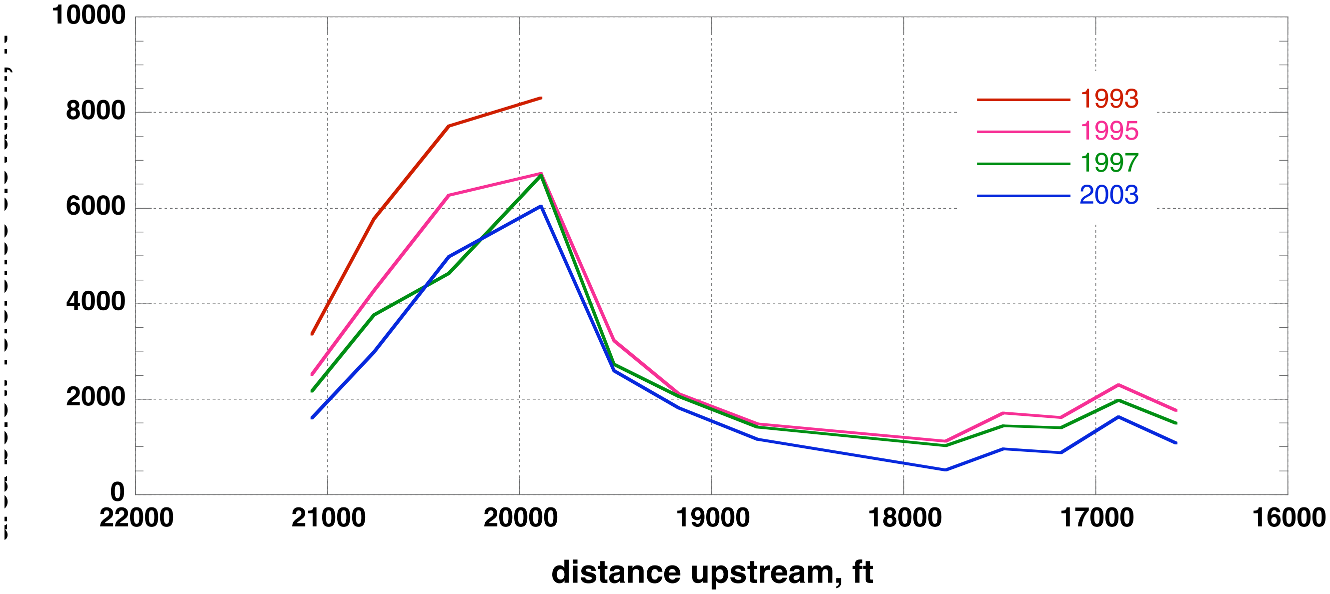

Emmerson Bar XS area vs streamwise distance
area below reference elevation, ft^2
9000
8000
7000
6000
5000
4000
3000
2000
1000
52500
52000
51500
51000
50500
50000
49500
distance upstream, ft
1994
1997
2003


Blue Lake Bar XS area vs streamwise distance


Christie Bar XS area vs streamwise distance


Johnson Bar XS area vs streamwise distance
area below reference elevation, ft^2
6000
4000
2000
38000
37000
36000
distance upstream, ft
1997
2003

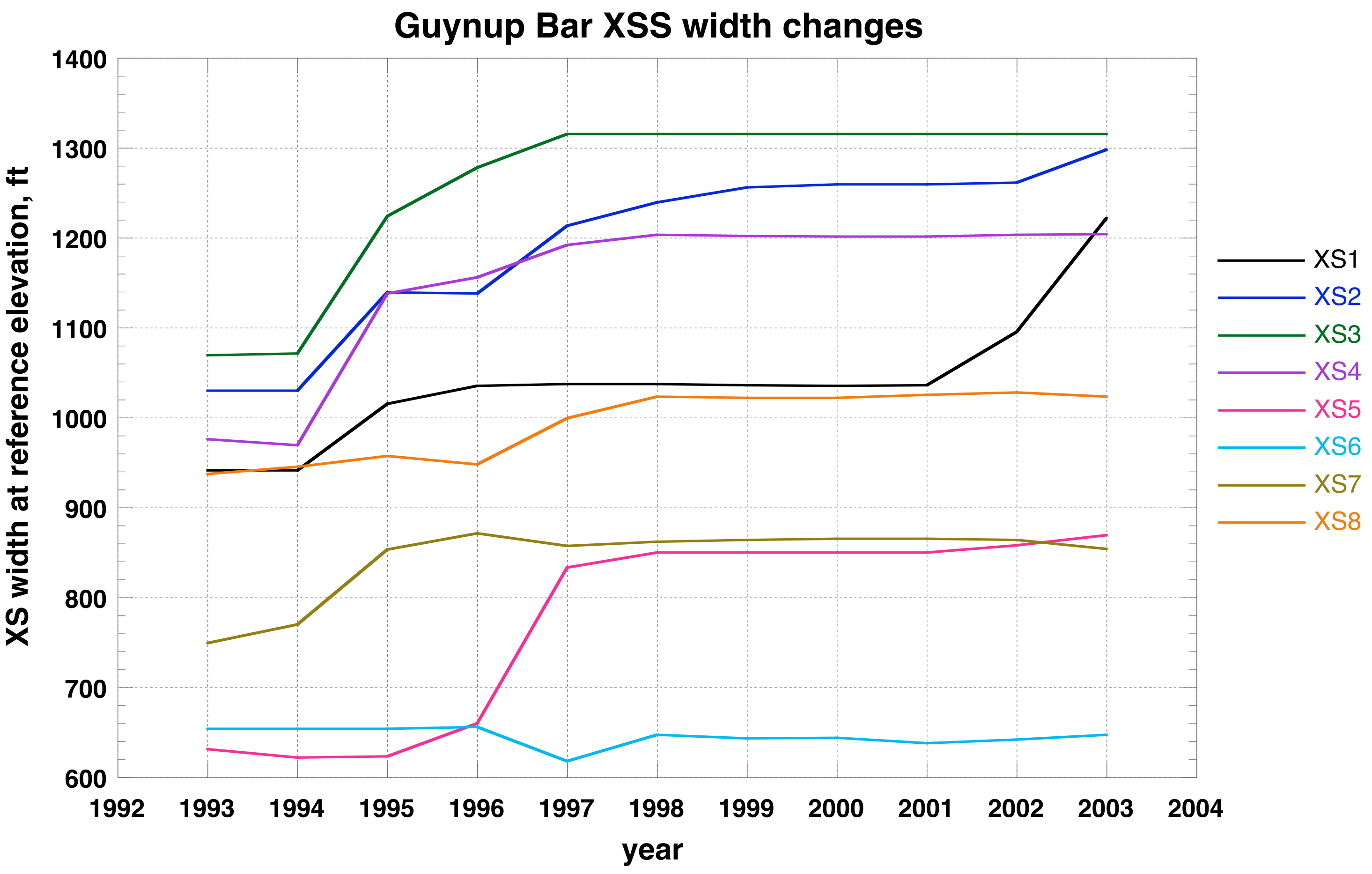

HBMWD and Essex Bar XS area vs streamwise distance
area below reference elevation, ft^2
10000
8000
6000
4000
2000
0
31000
30000
29000
28000
27000
26000
25000
24000
23000
22000
distance upstream, ft
1993
1997
2003

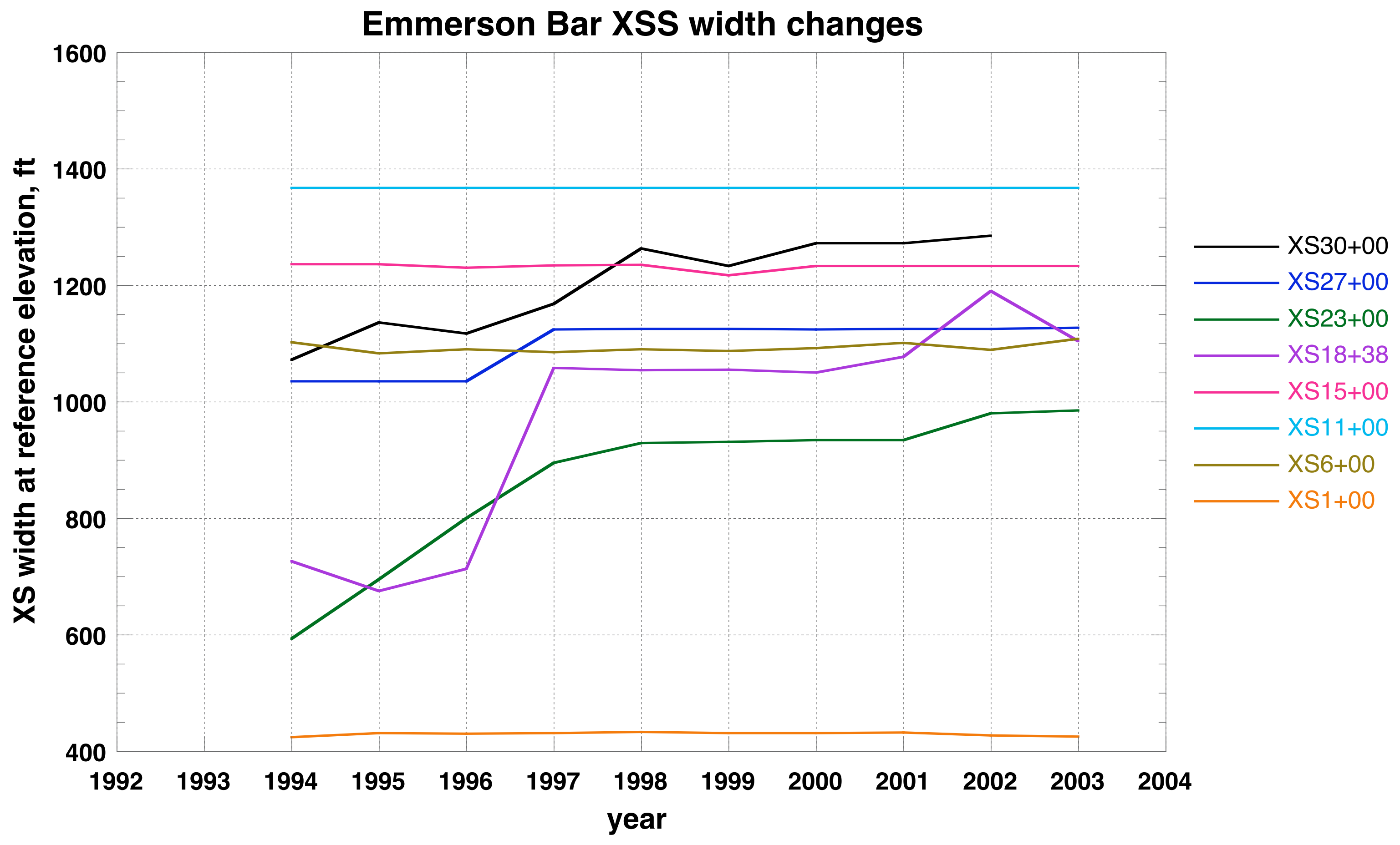


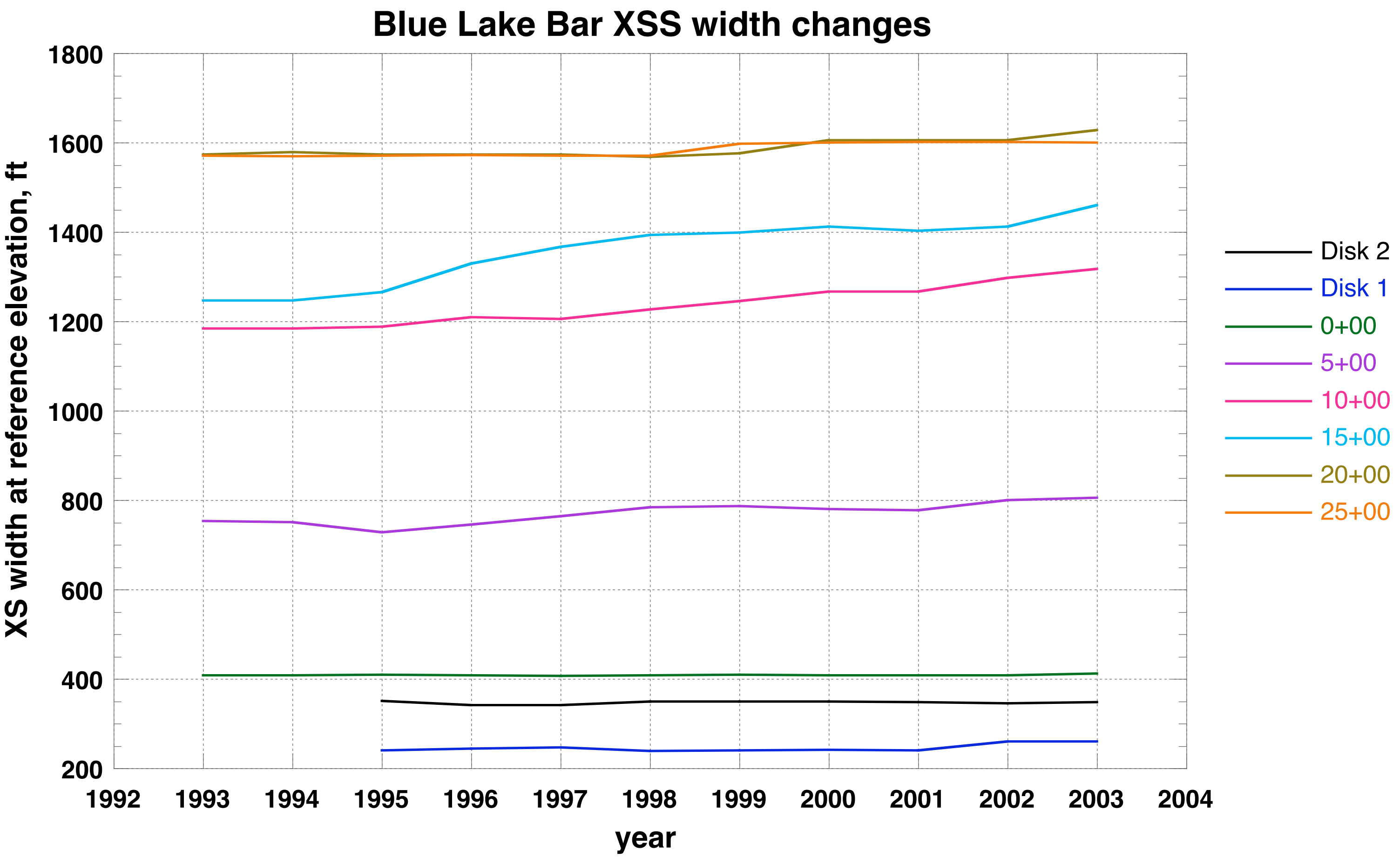
Johnson-Spini, Miller-Almquist and O'Neill Bars
XS area vs streamwise distance

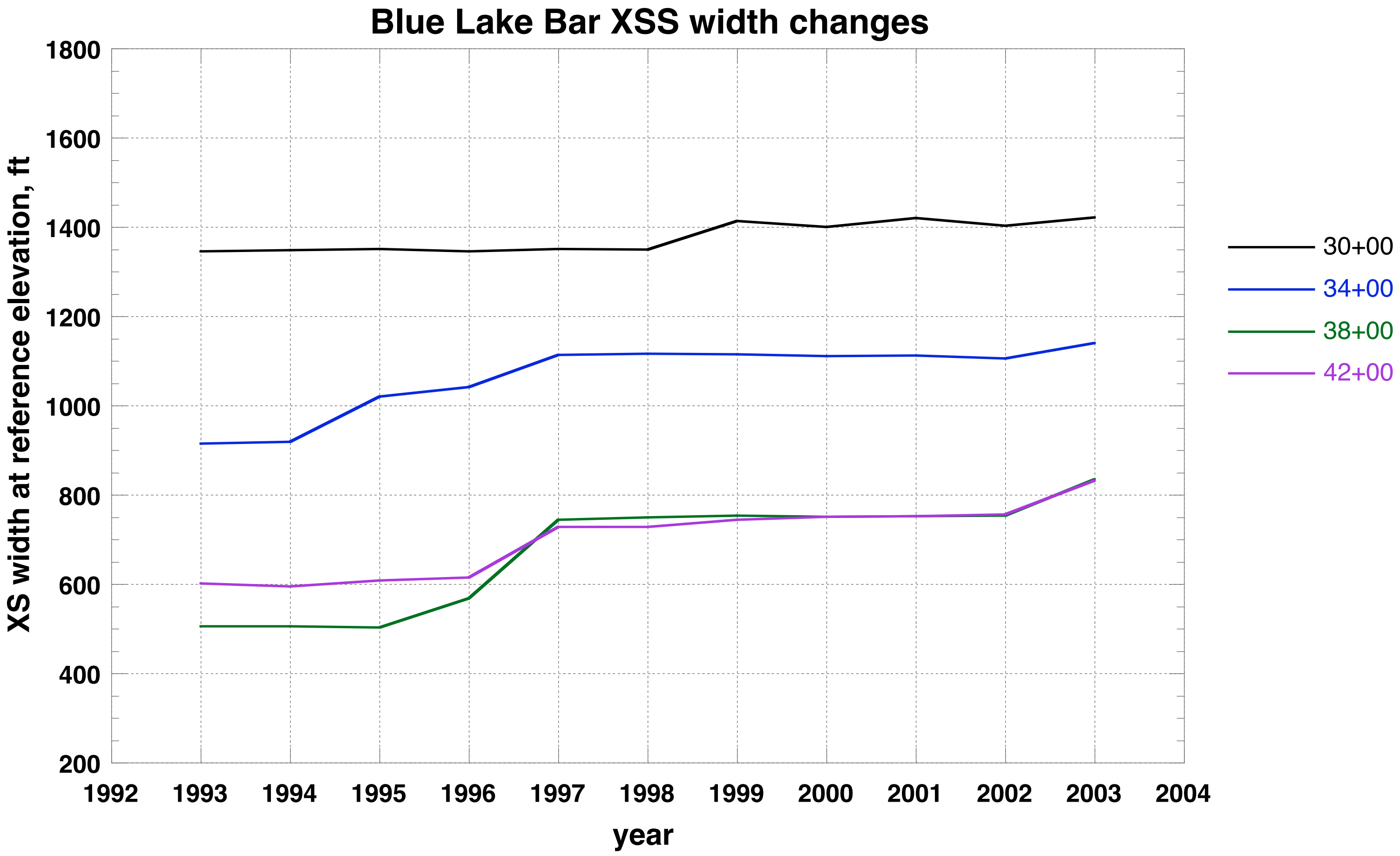
Appendix G

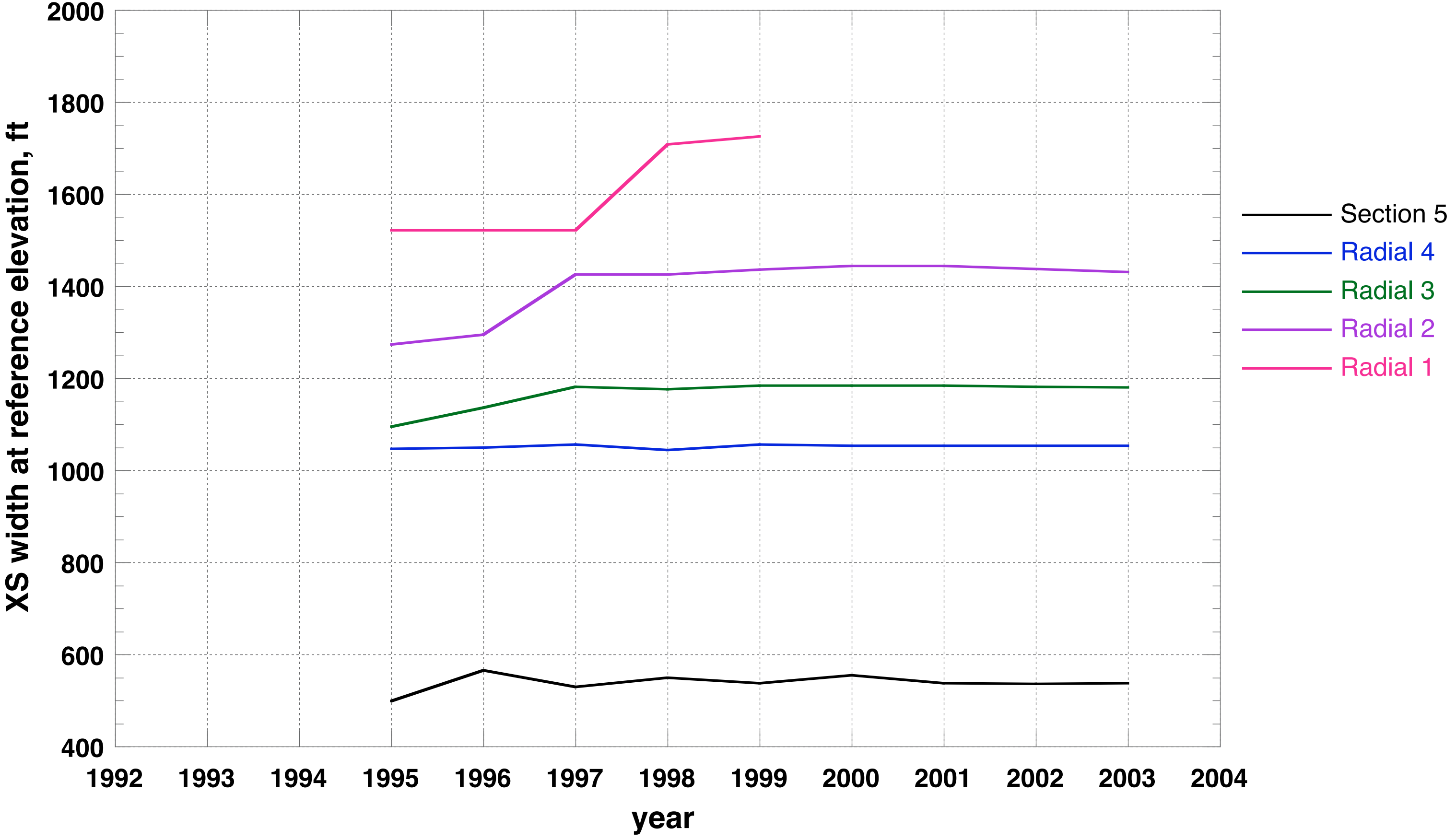
XS width vs time, by bars

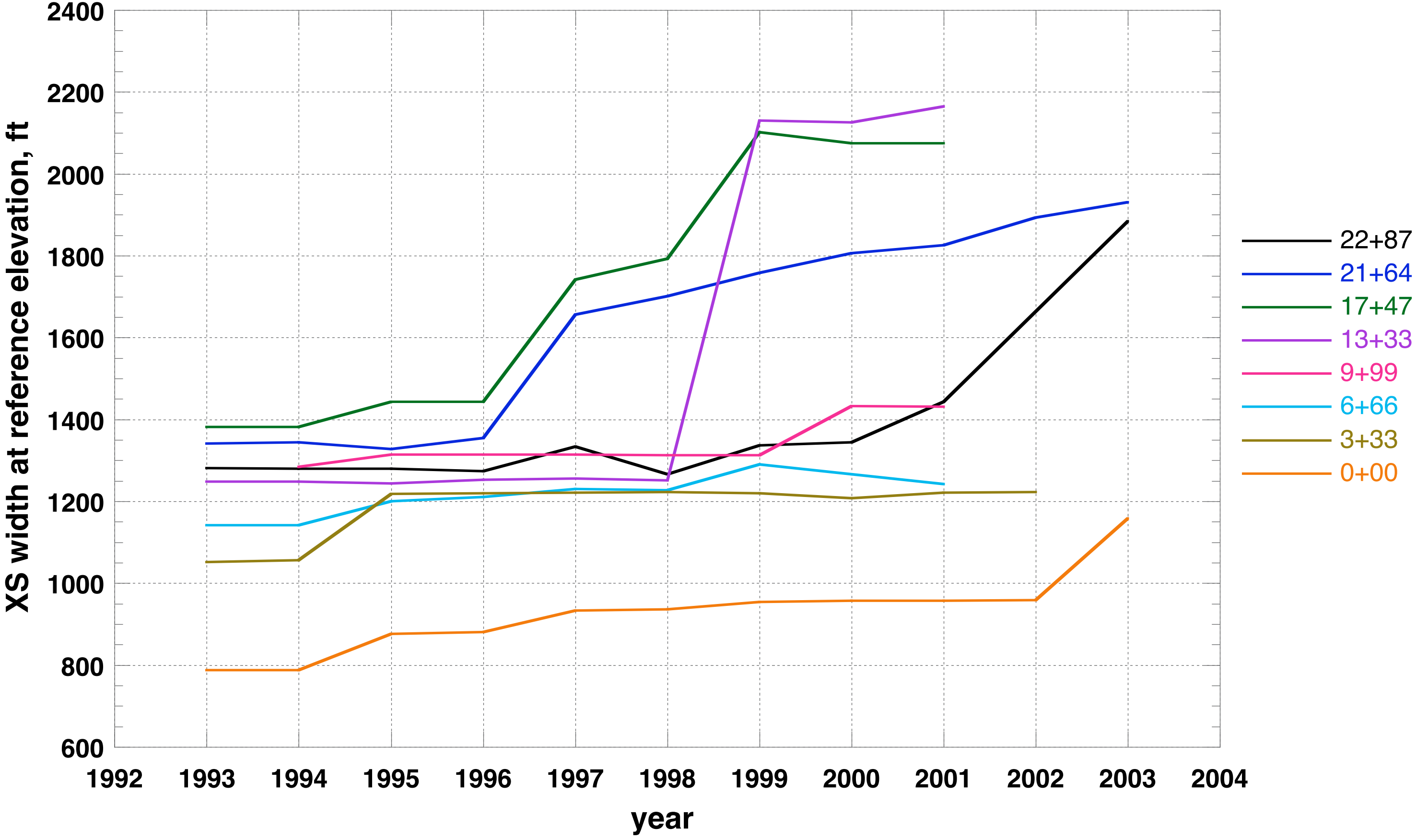

Guynup Bar XSS width changes
XS width at reference elevation, ft
1400
1300
1200
1100
1000
900
800
700
600
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
XS1
XS2
XS3
XS4
XS5
XS6
XS7
XS8

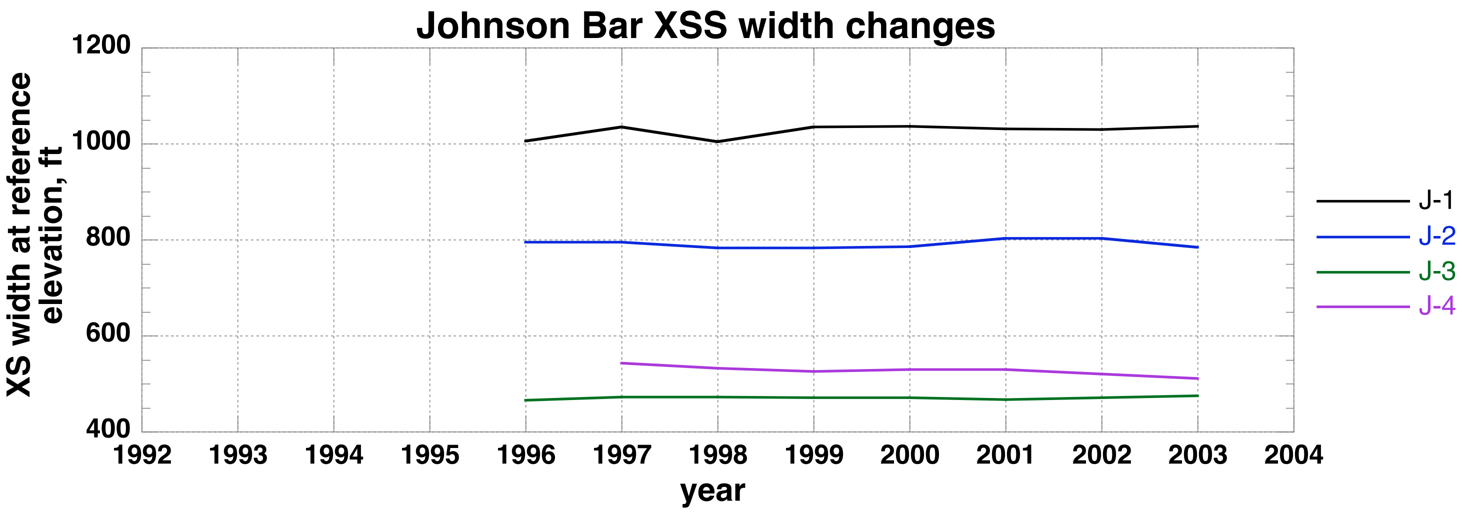

Emmerson Bar XSS width changes
XS width at reference elevation, ft
1600
1400
1200
1000
800
600
400
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
XS30+00
XS27+00
XS23+00
XS18+38
XS15+00
XS11+00
XS6+00
XS1+00

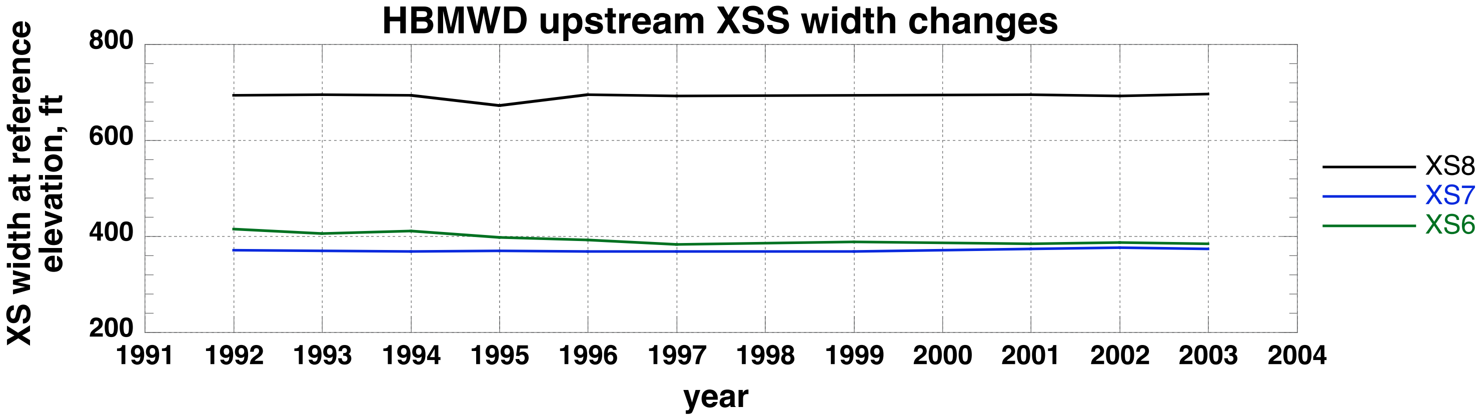

Blue Lake Bar XSS width changes
XS width at reference elevation, ft
1800
1600
1400
1200
1000
800
600
400
200
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
Disk 2
Disk 1
0+00
5+00
10+00
15+00
20+00
25+00

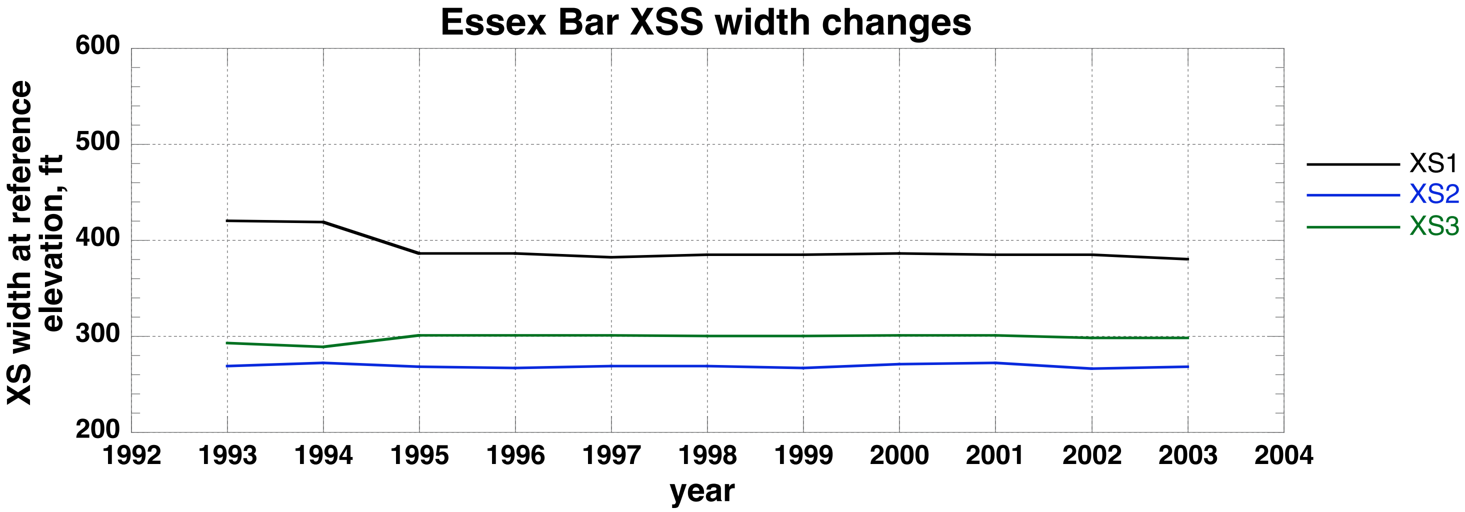

Blue Lake Bar XSS width changes
XS width at reference elevation, ft
1800
1600
1400
1200
1000
800
600
400
200
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
30+00
34+00
38+00
42+00

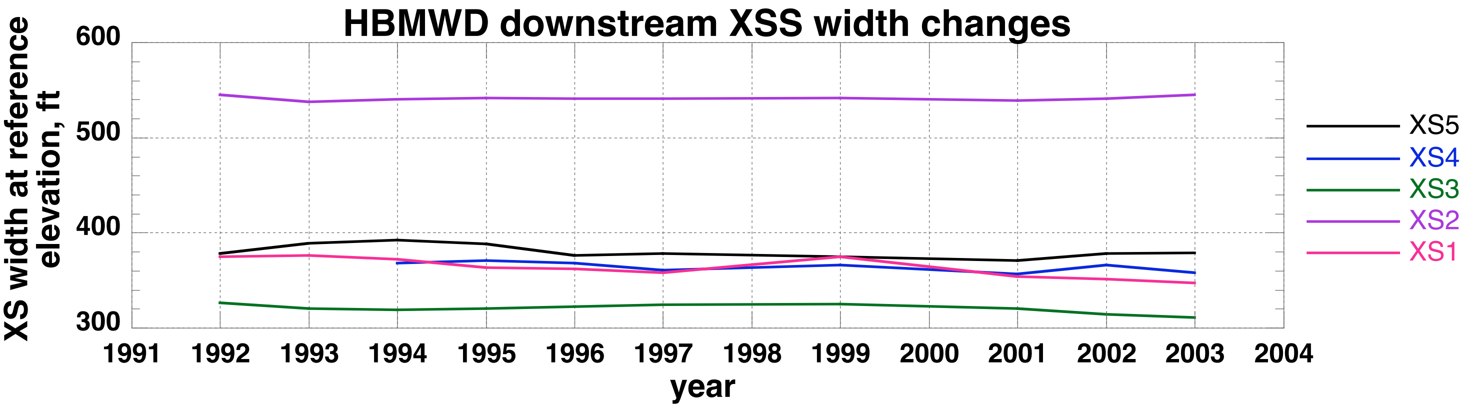

Christie (Leavey) Bar XSS width changes

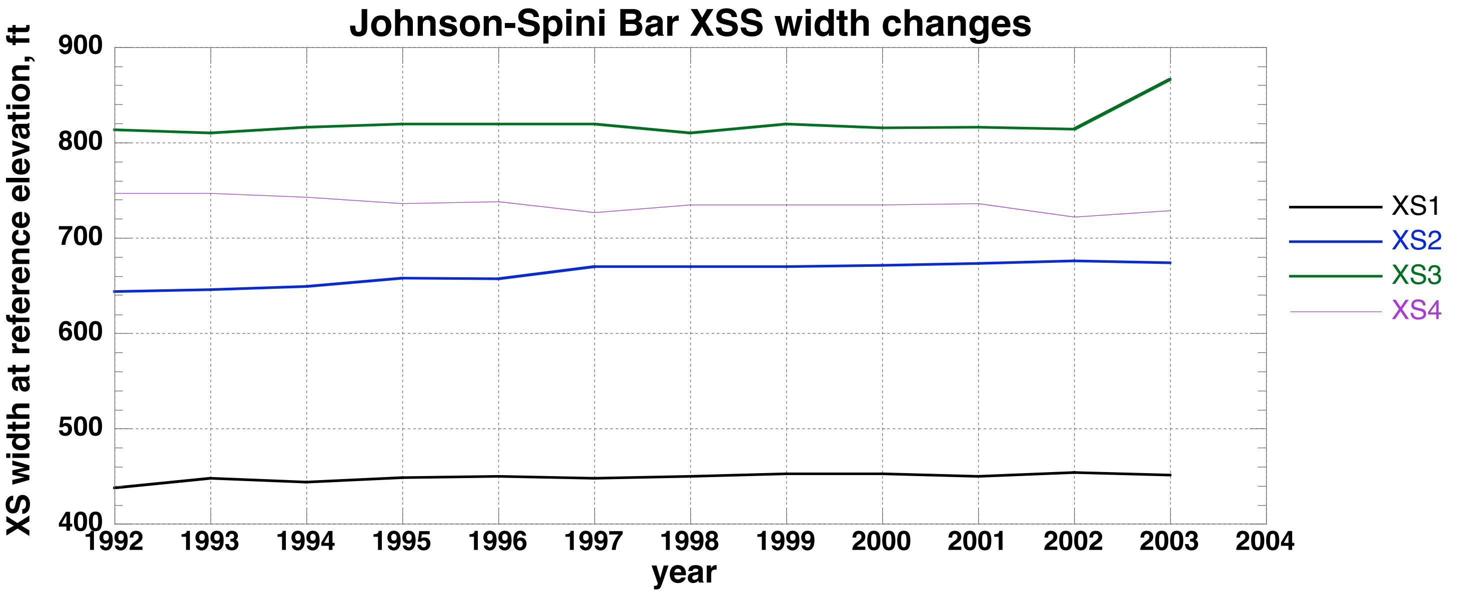

Christie Bar XSS width changes

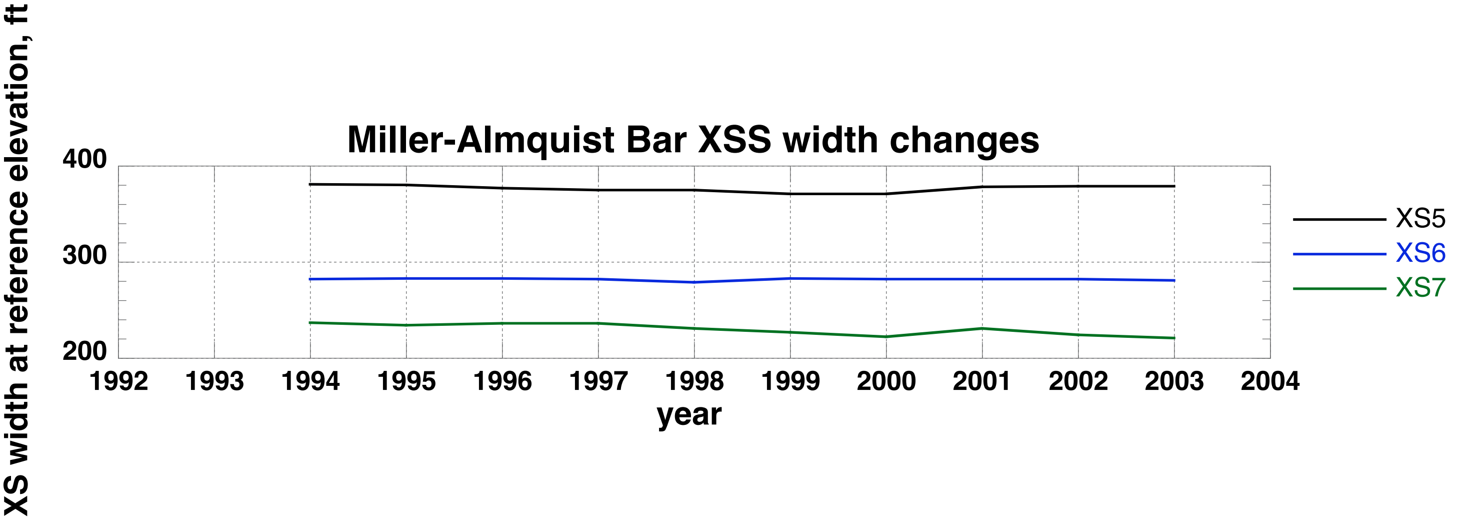

Johnson Bar XSS width changes
XS width at reference elevation, ft
1200
1000
800
600
400
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
J-1
J-2
J-3
J-4

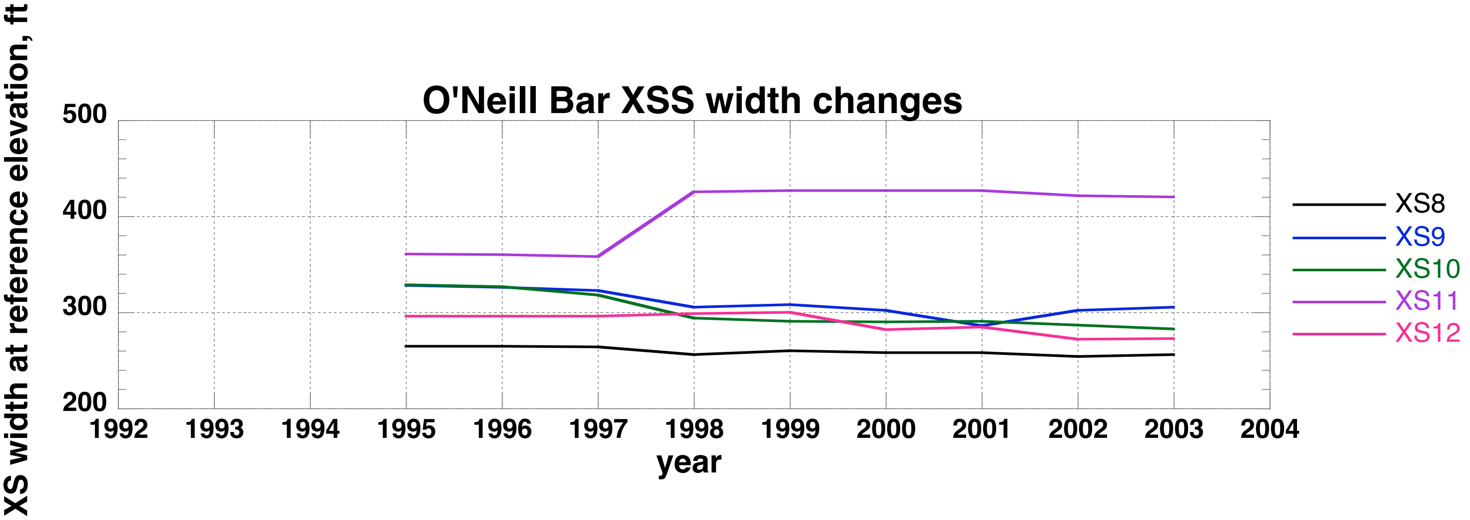

HBMWD upstream XSS width changes
XS width at reference elevation, ft
800
600
400
200
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
XS8
XS7
XS6


Essex Bar XSS width changes
XS width at reference elevation, ft
600
500
400
300
200
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
XS1
XS2
XS3


HBMWD downstream XSS width changes
XS width at reference elevation, ft
600
500
400
300
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
year
XS5
XS4
XS3
XS2
XS1

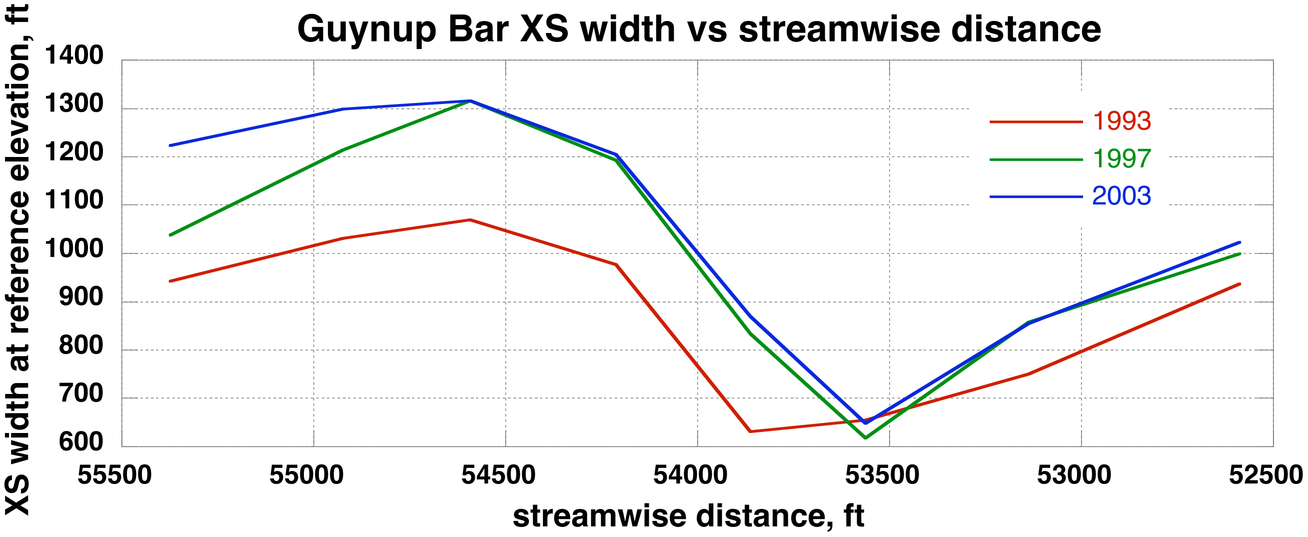

Johnson-Spini Bar XSS width changes

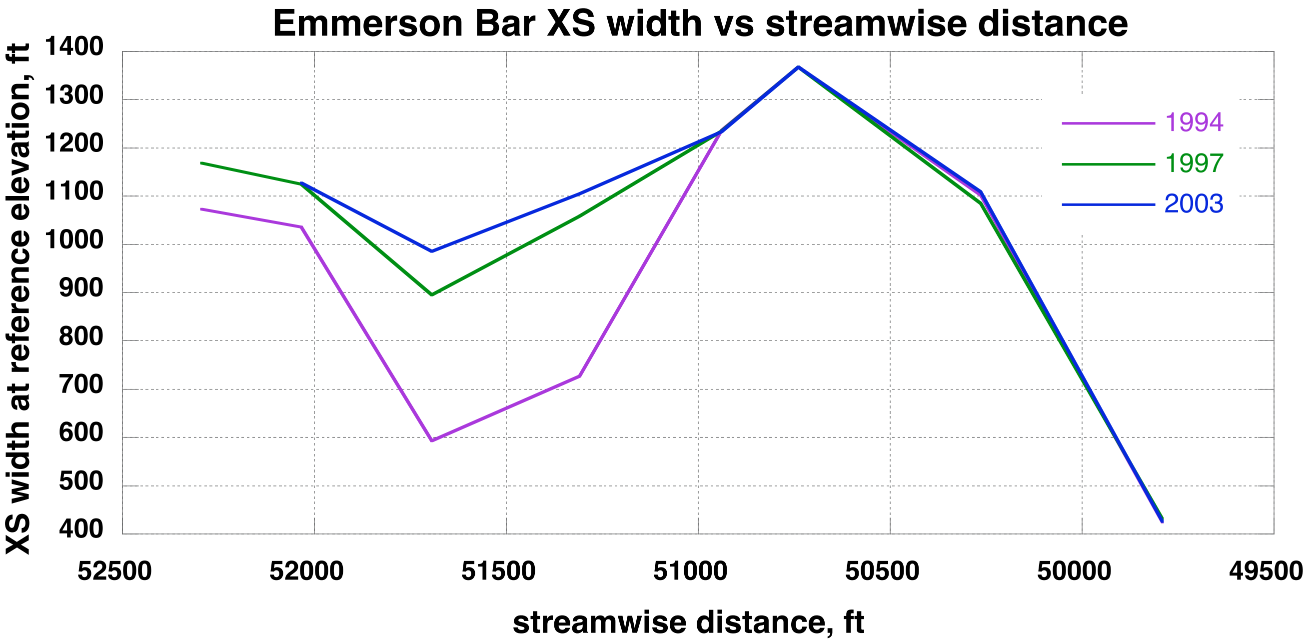

Miller-Almquist Bar XSS width changes

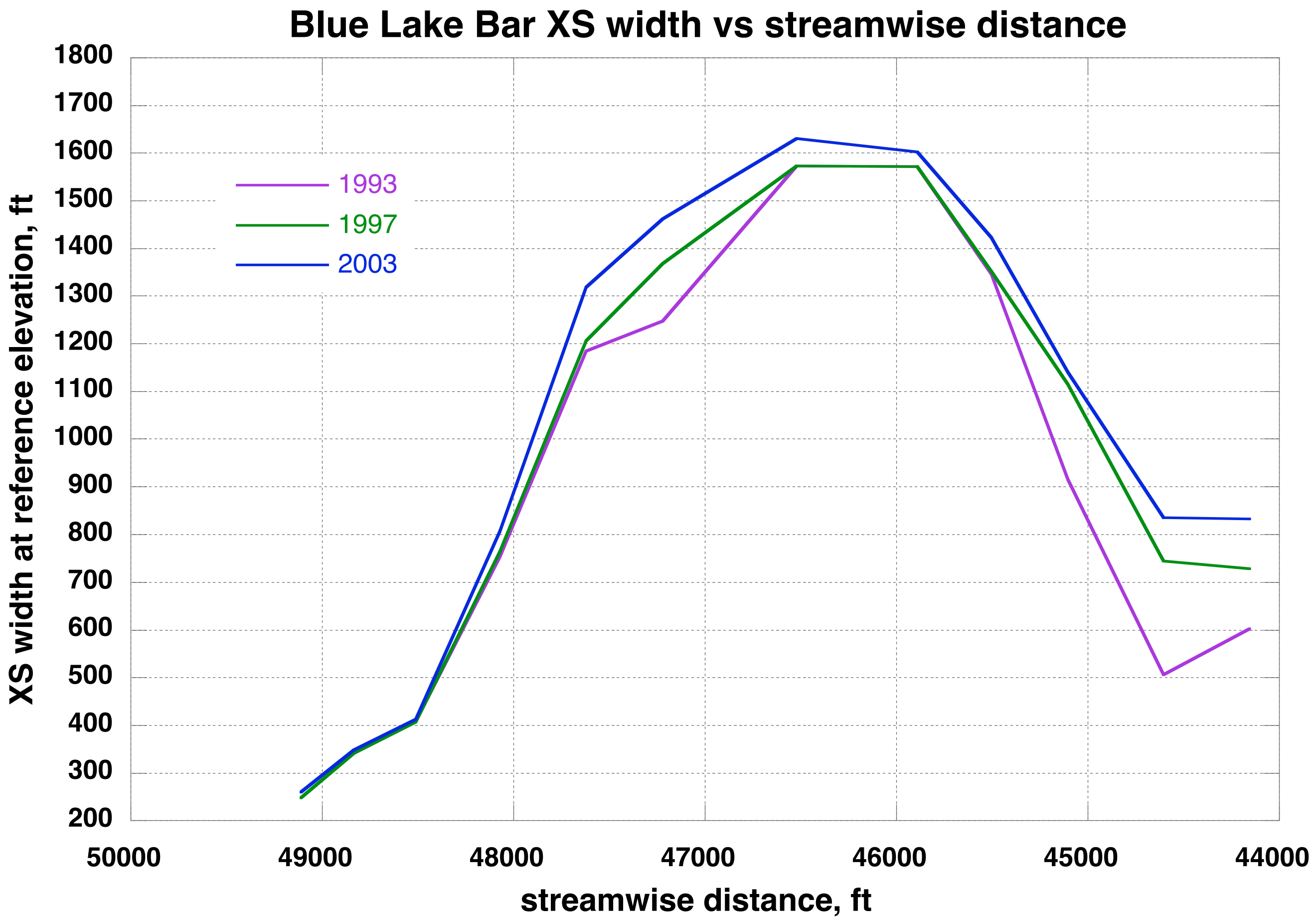

O'Neill Bar XSS width changes

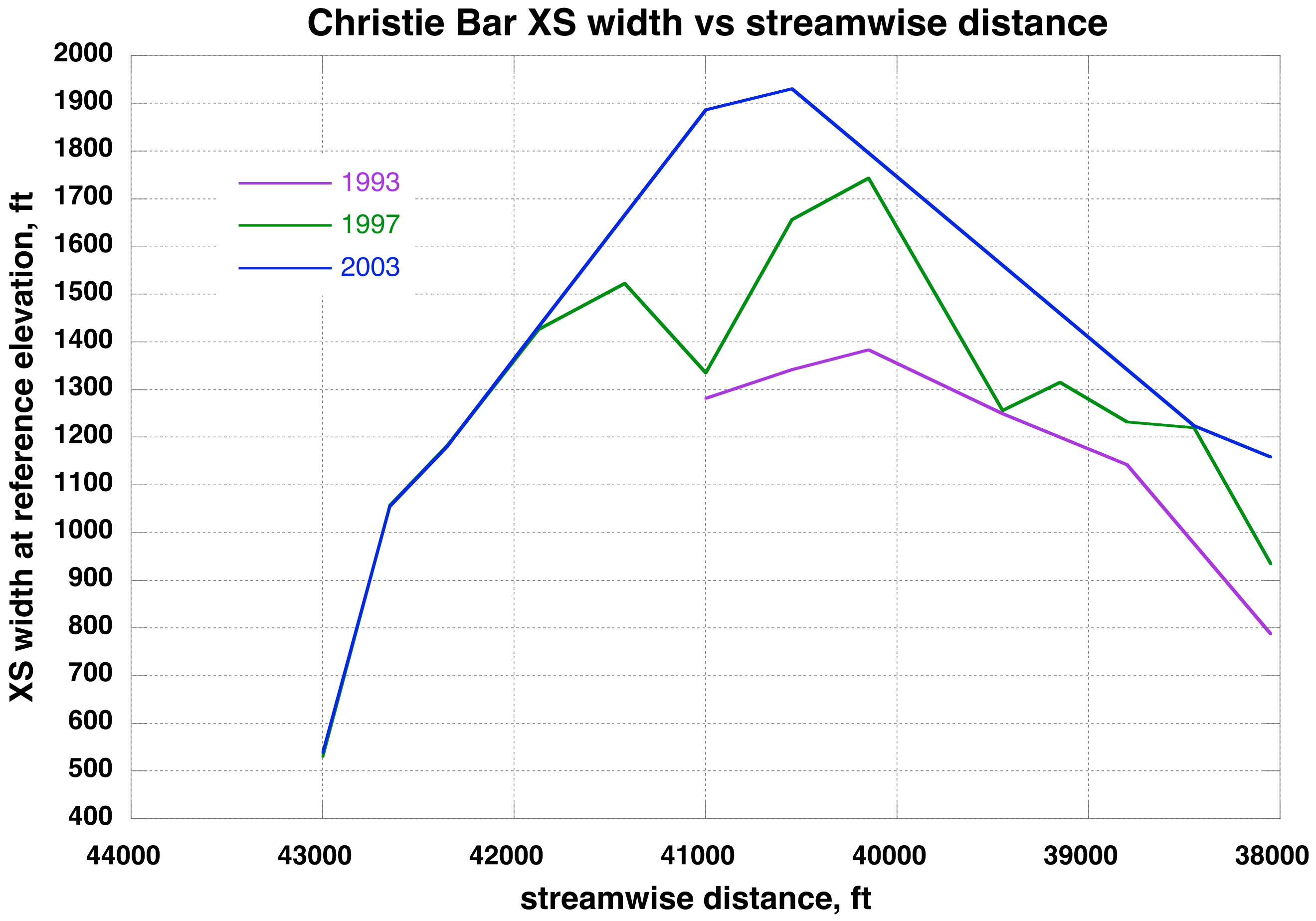
Appendix H

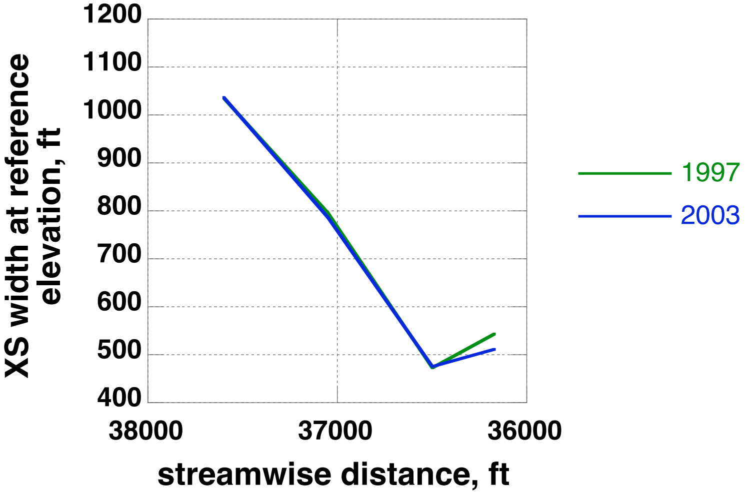
XS width vs streamwise distance, by bars
1993, 1997, 2003


Guynup Bar XS width vs streamwise distance
XS width at reference elevation, ft
1400
1300
1200
1100
1000
900
800
700
600
55500
55000
54500
54000
53500
53000
52500
streamwise distance, ft
1993
1997
2003

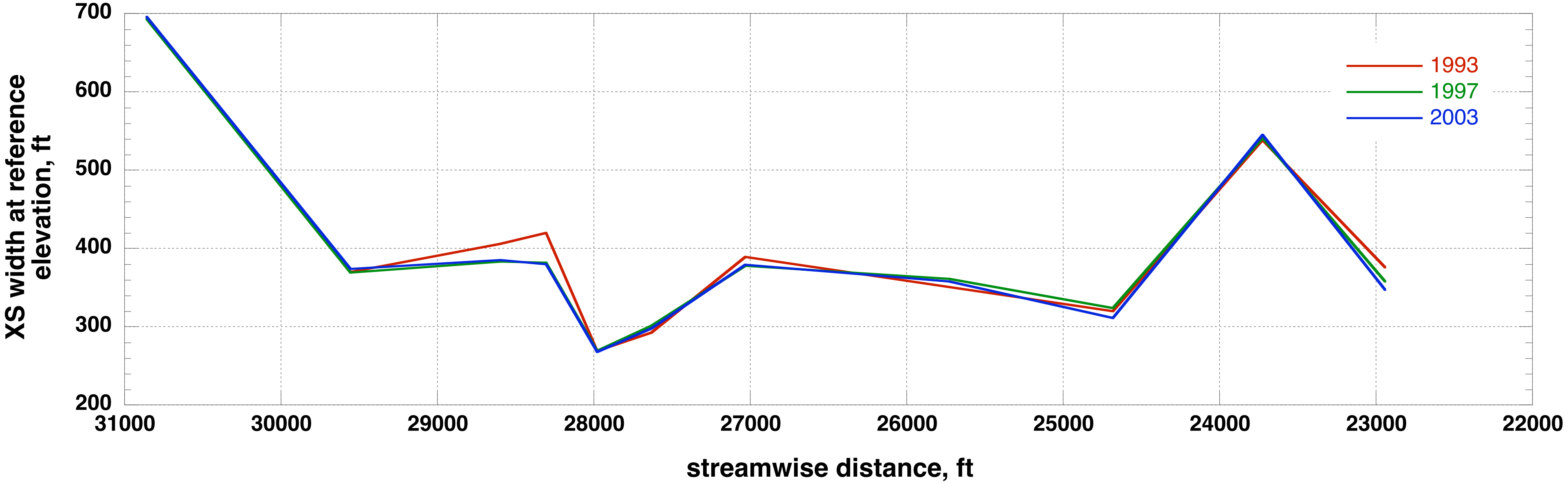

Emmerson Bar XS width vs streamwise distance
XS width at reference elevation, ft
1400
1300
1200
1100
1000
900
800
700
600
500
400
52500
52000
51500
51000
50500
50000
49500
streamwise distance, ft
1994
1997
2003


Blue Lake Bar XS width vs streamwise distance
XS width at reference elevation, ft
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
50000
49000
48000
47000
46000
45000
44000
streamwise distance, ft
1993
1997
2003


Christie Bar XS width vs streamwise distance
XS width at reference elevation, ft
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
44000
43000
42000
41000
40000
39000
38000
streamwise distance, ft
1993
1997
2003

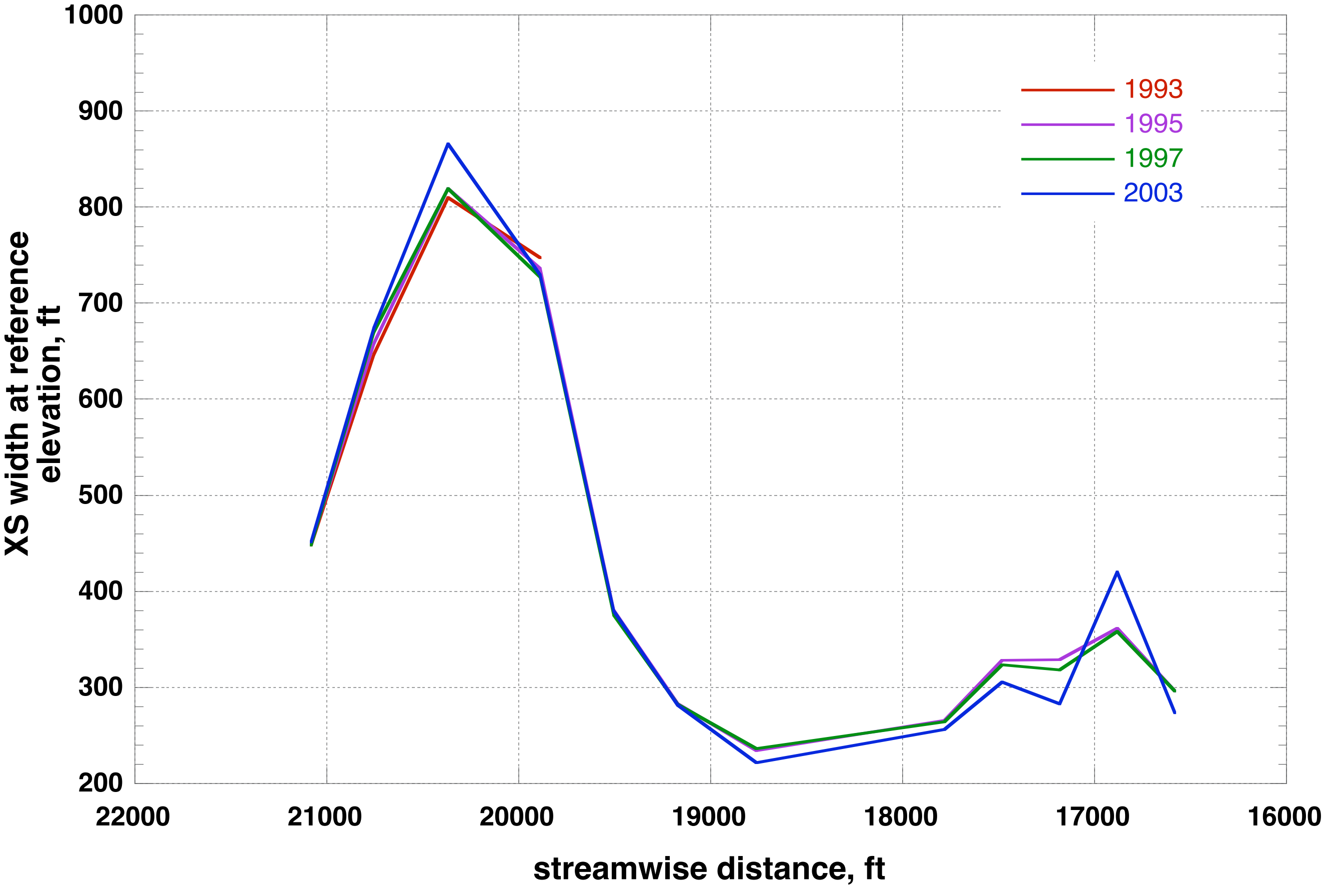


Johnson Bar XS width vs streamwise distance



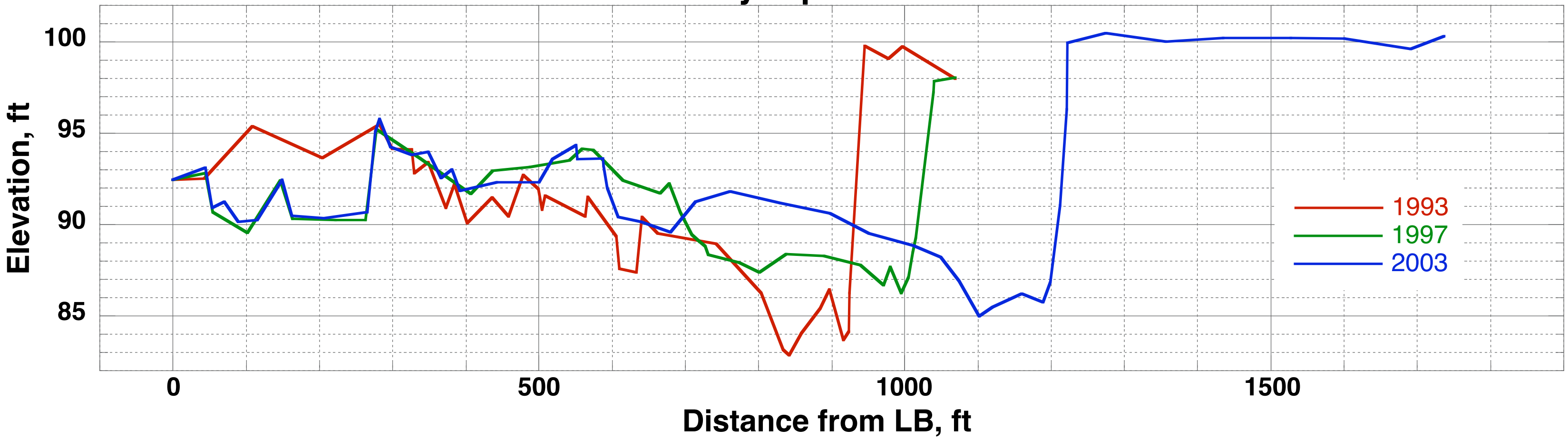
HBMWD and Essex Bar XS width vs streamwise distance

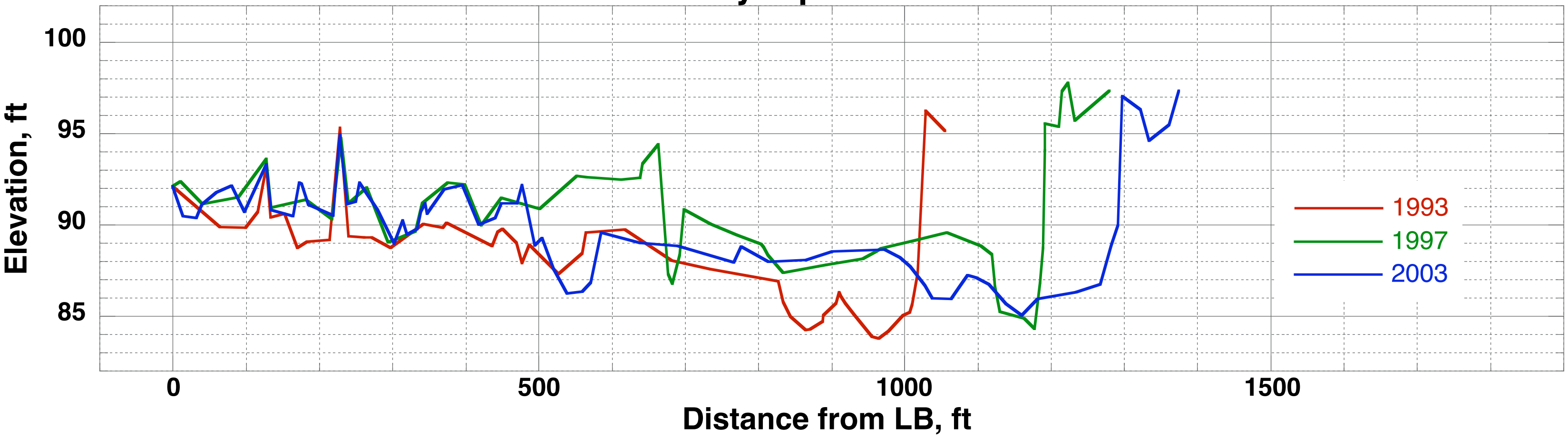
Johnson-Spini, Miller-Almquist and O'Neill Bar
XS width vs streamwise distance

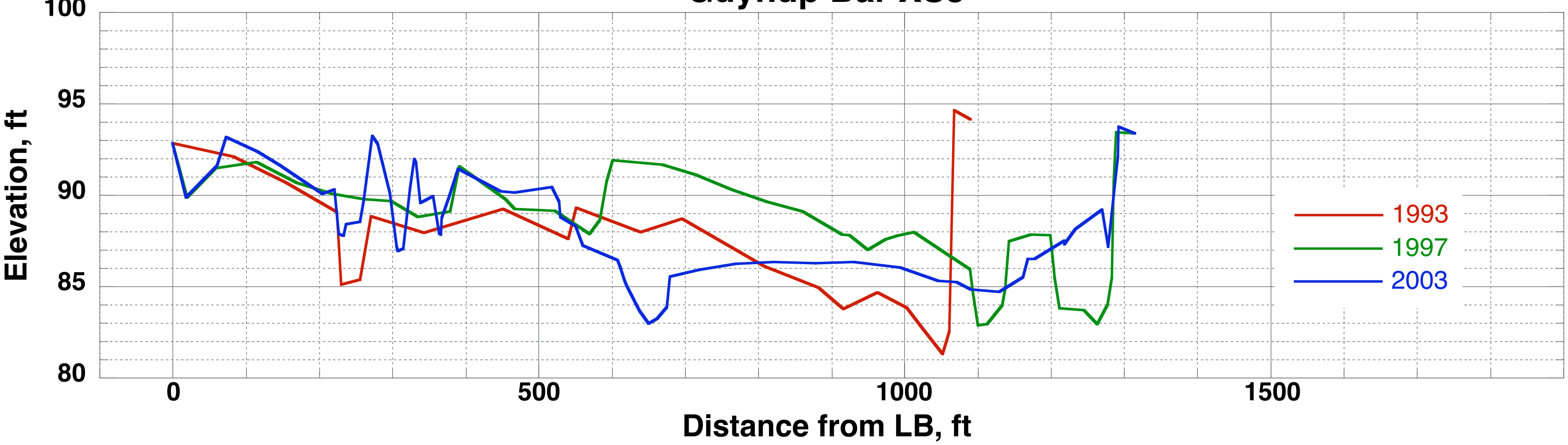


Appendix I

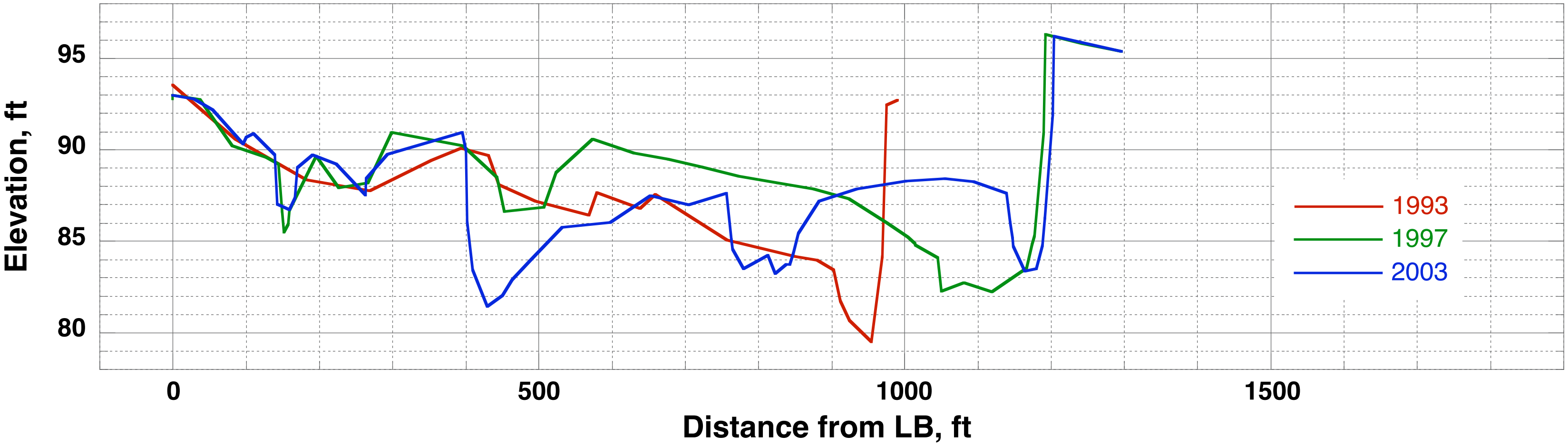
Mad R Cross-Sections
1993, 1997, 2003


Guynup Bar XS1

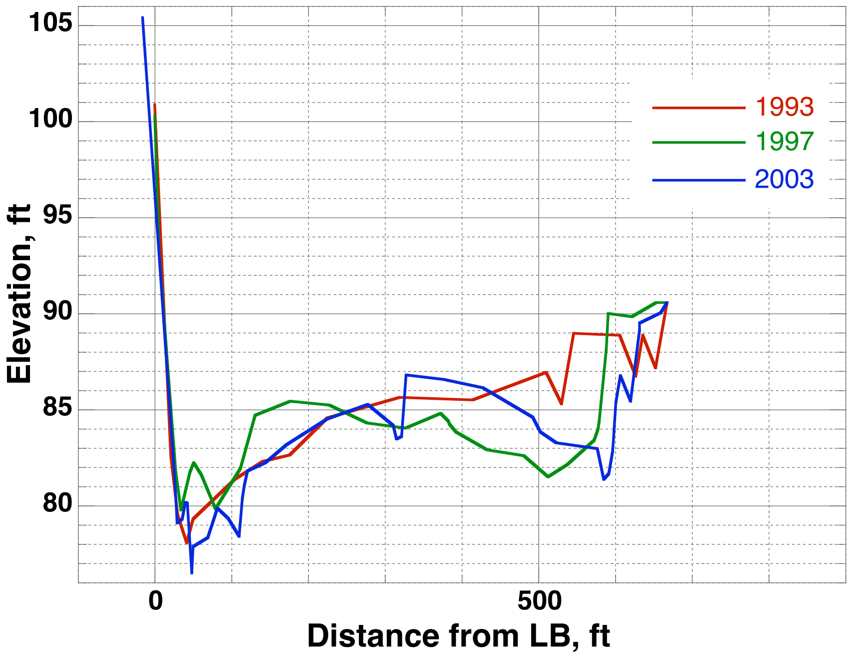

Guynup Bar XS2

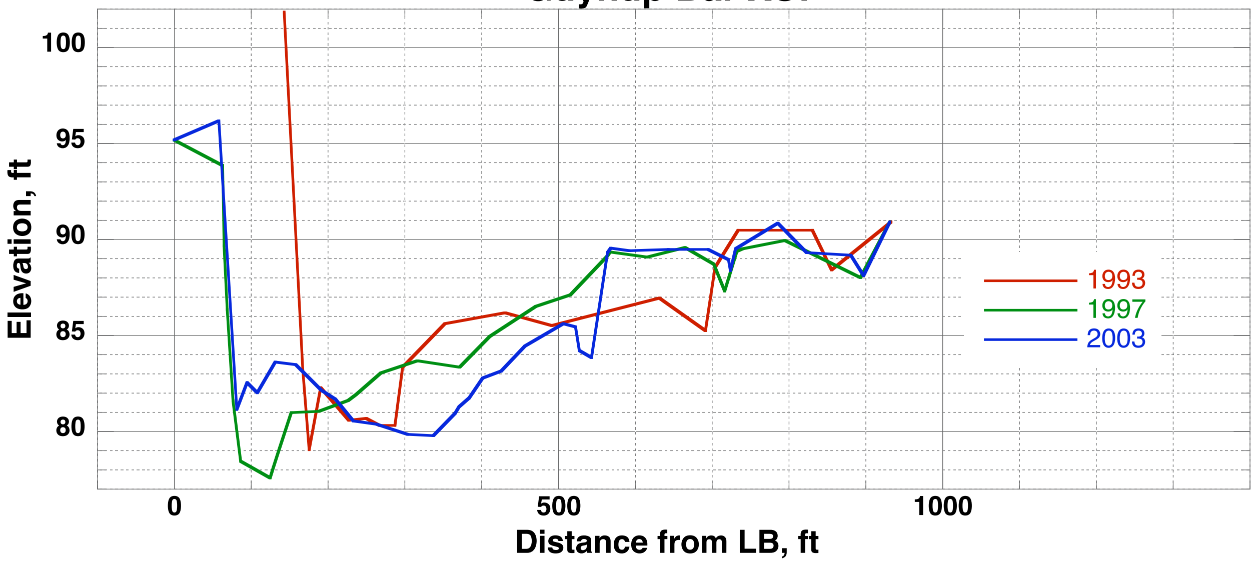

Guynup Bar XS3

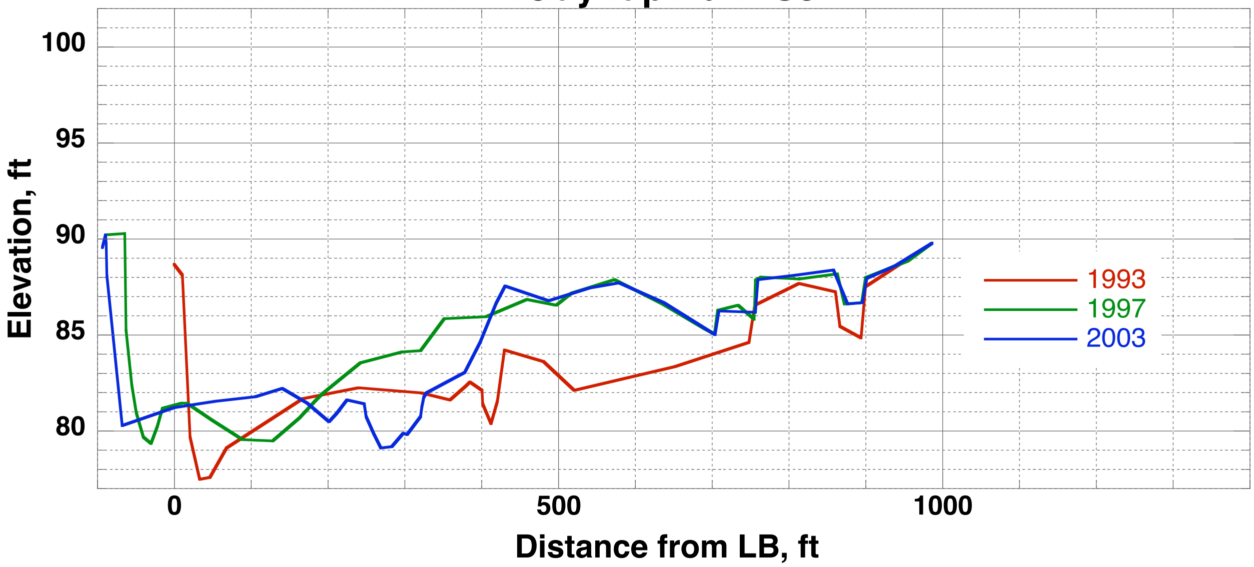
Guynup Bar XS4

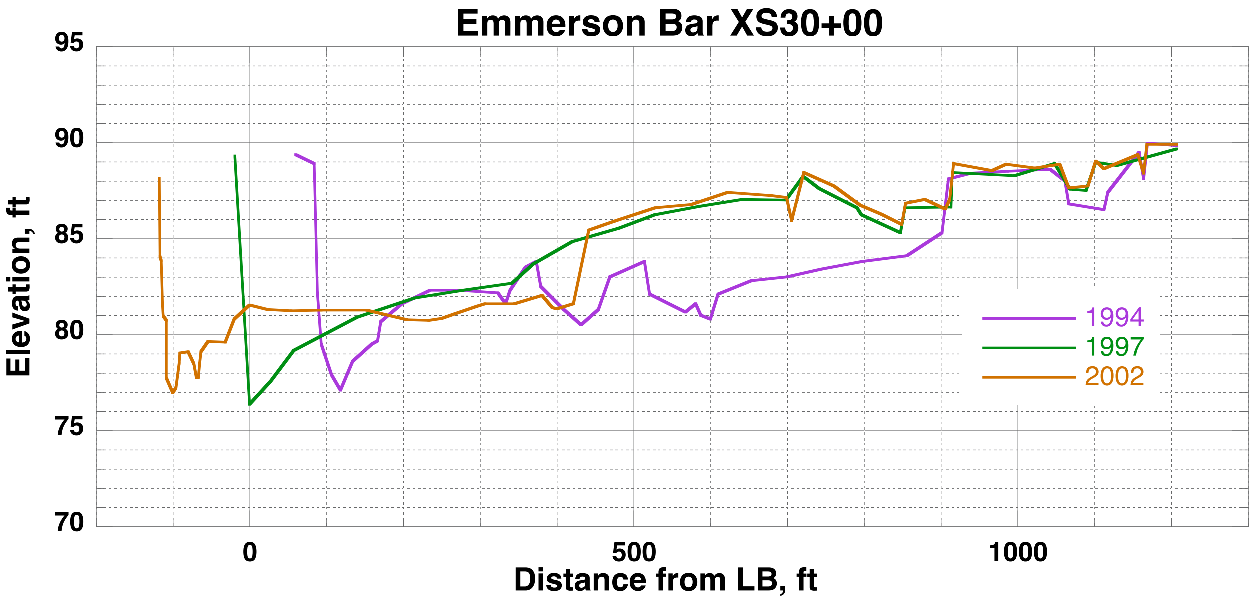


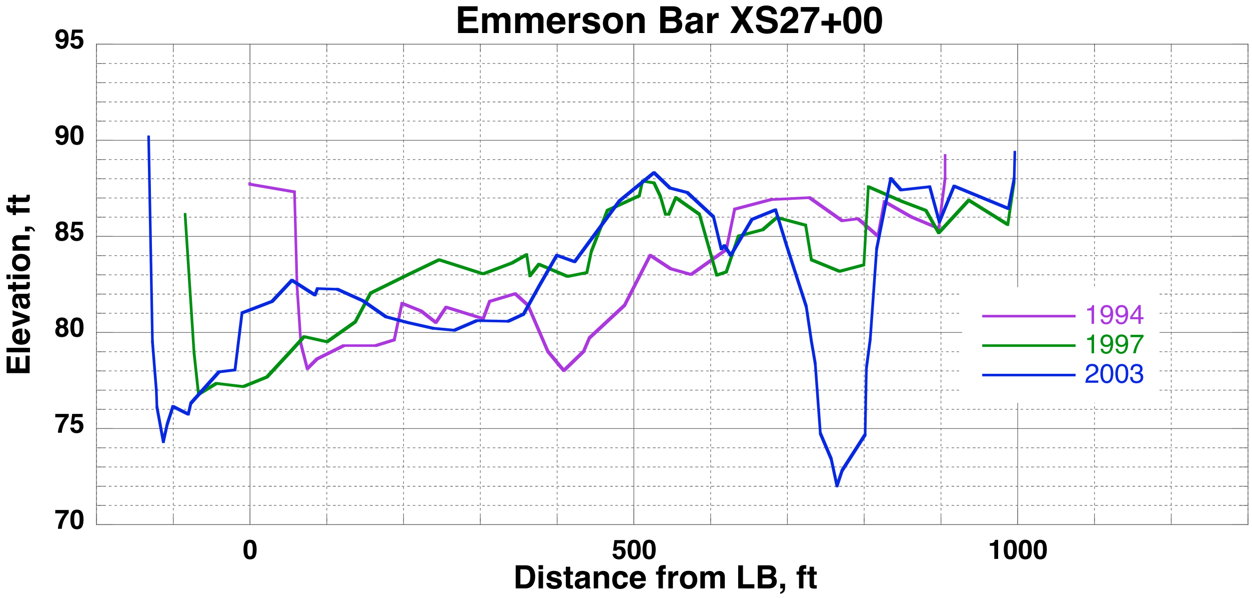
Guynup Bar XS5

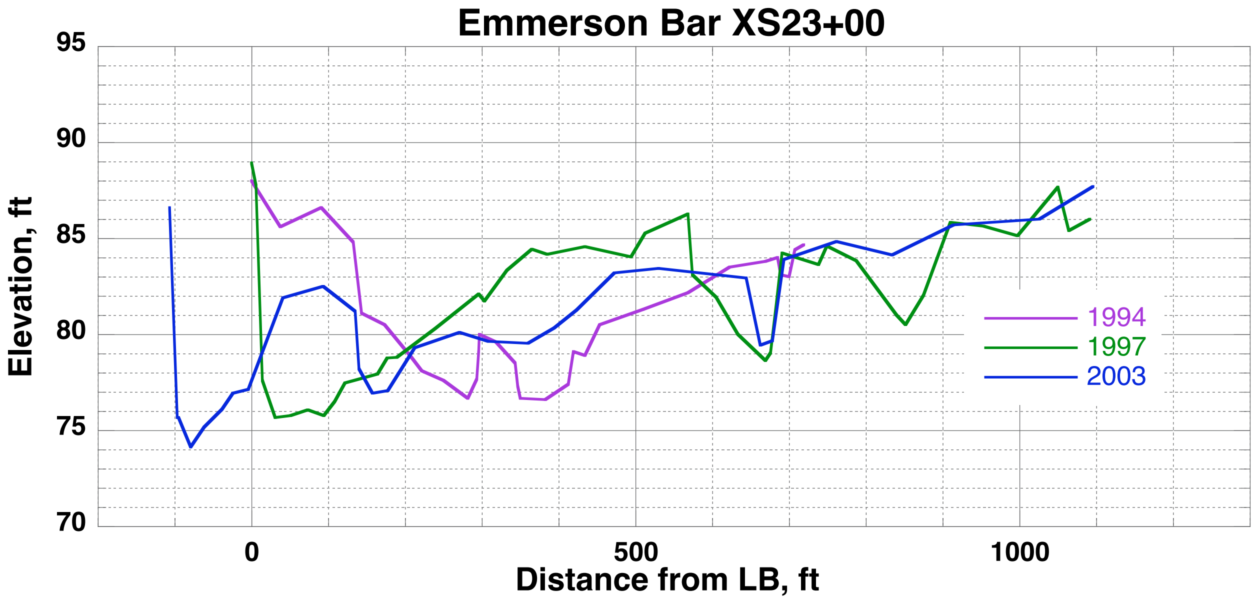

Guynup Bar XS6

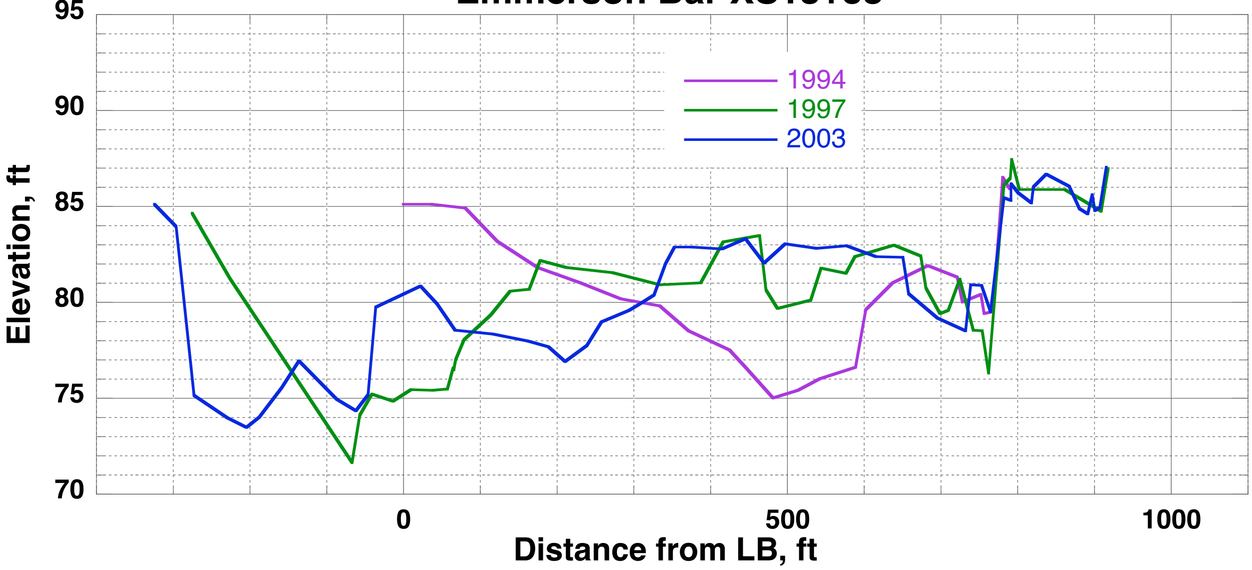

Guynup Bar XS7


Guynup Bar XS8

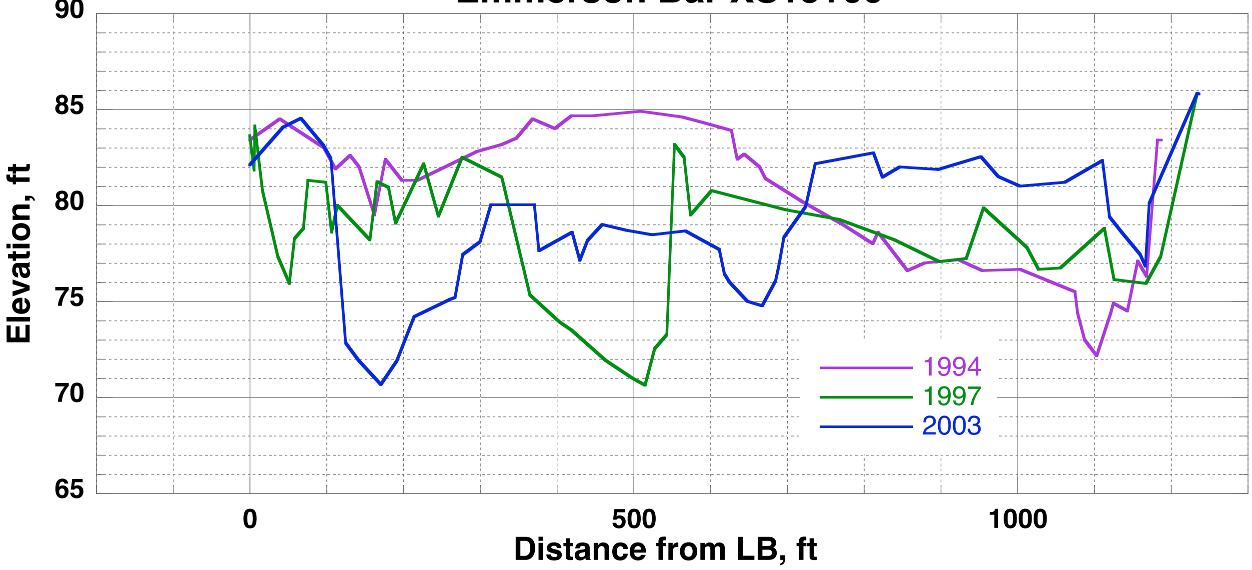

Emmerson Bar XS30+00
Elevation, ft
Distance from LB, ft
95
90
85
80
75
70
0
500
1000
1994
1997
2002


Emmerson Bar XS27+00
Elevation, ft
Distance from LB, ft
95
90
85
80
75
70
0
500
1000
1994
1997
2003

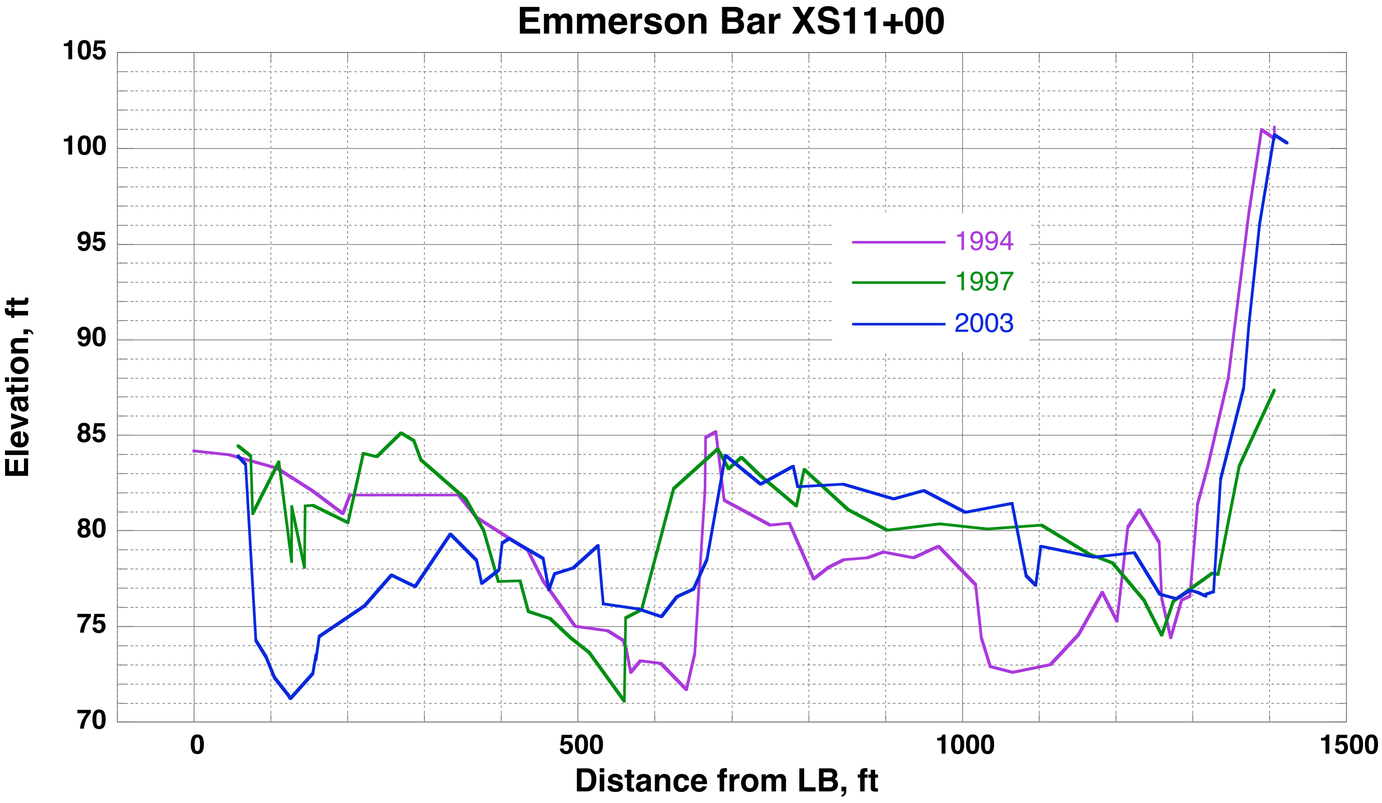

Emmerson Bar XS23+00
Elevation, ft
Distance from LB, ft
95
90
85
80
75
70
0
500
1000
1994
1997
2003

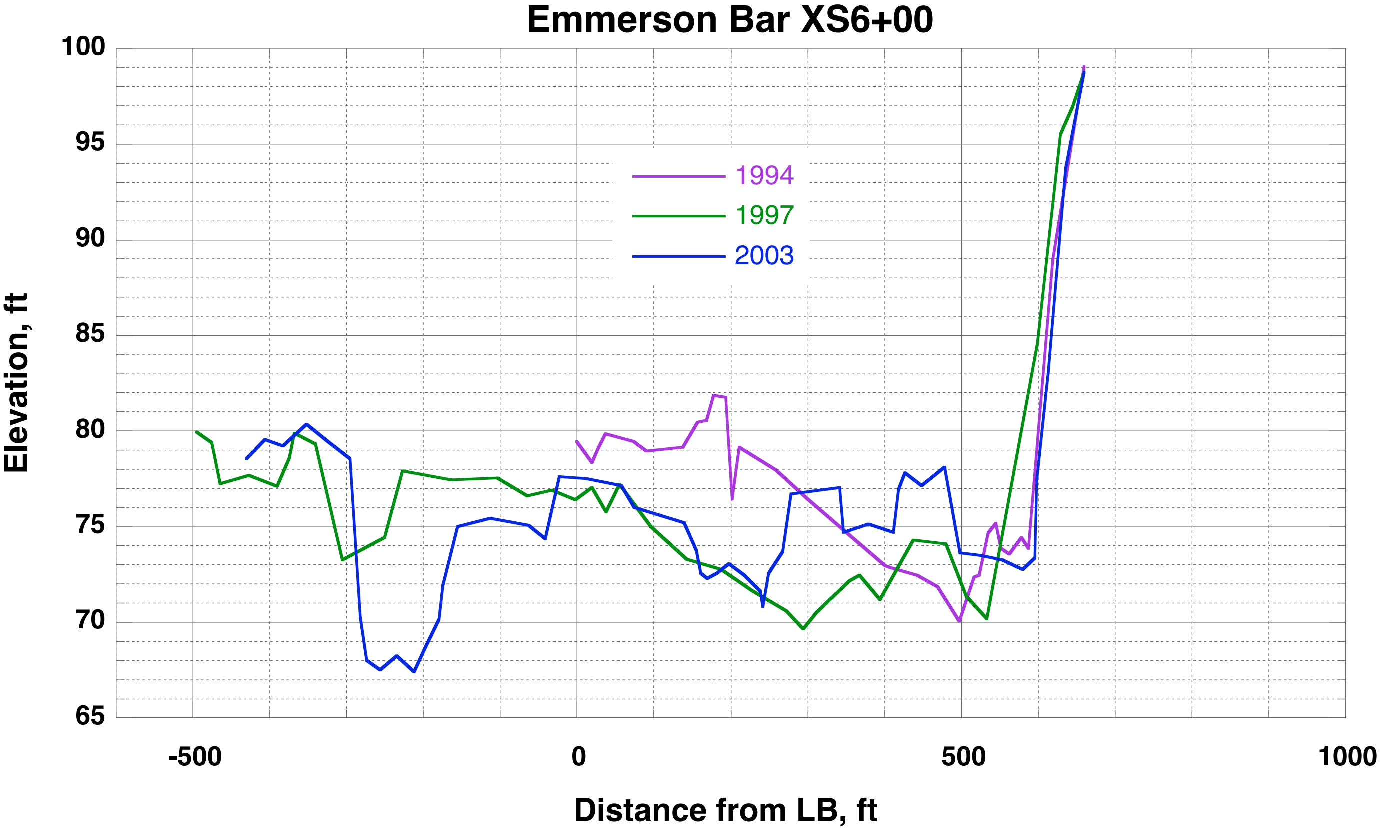


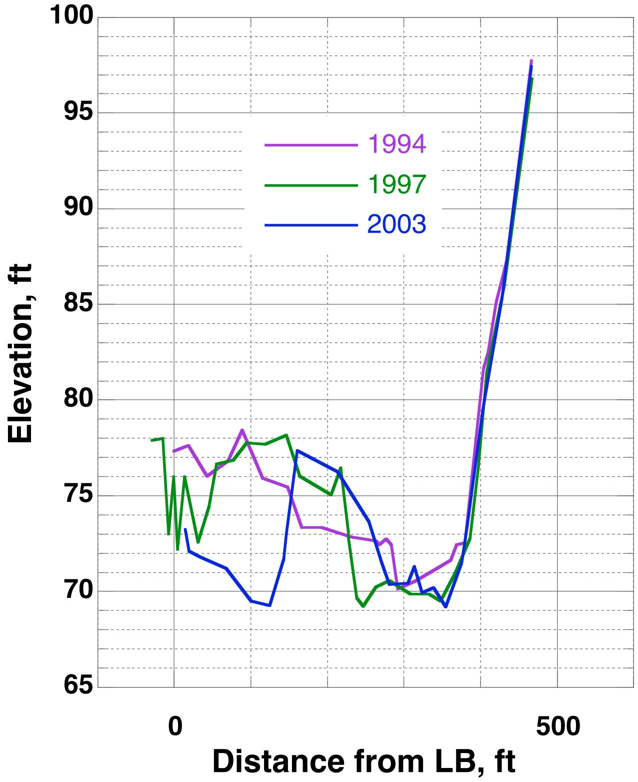
Emmerson Bar XS18+38

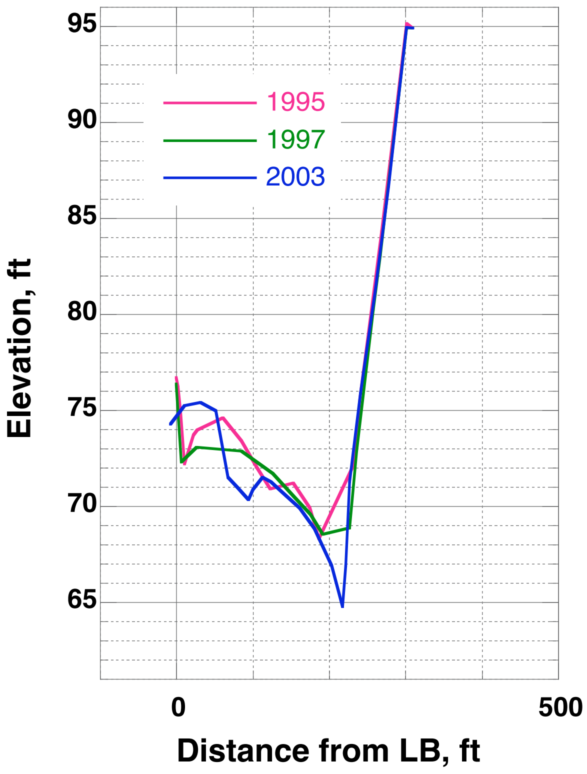


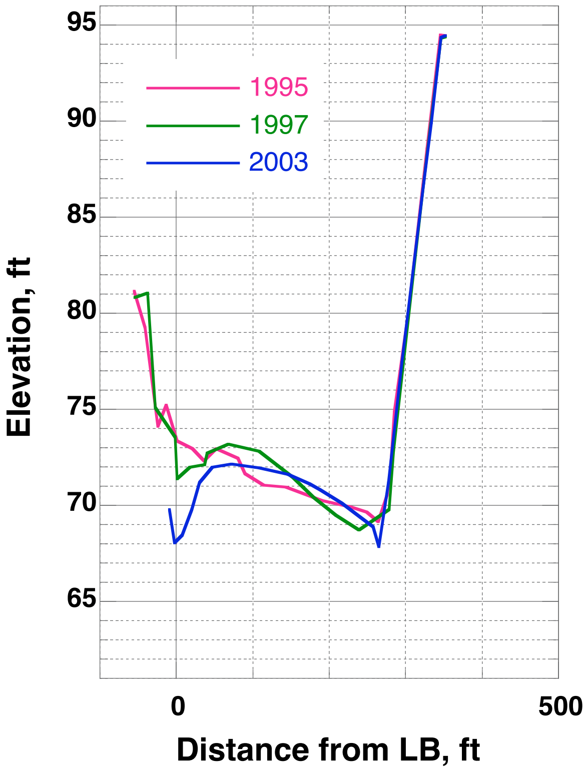
Emmerson Bar XS15+00


Emmerson Bar XS11+00
105
100
95
90
85
80
75
70
0
500
1000
1500
Distance from LB, ft
Elevation, ft
1994
1997
2003

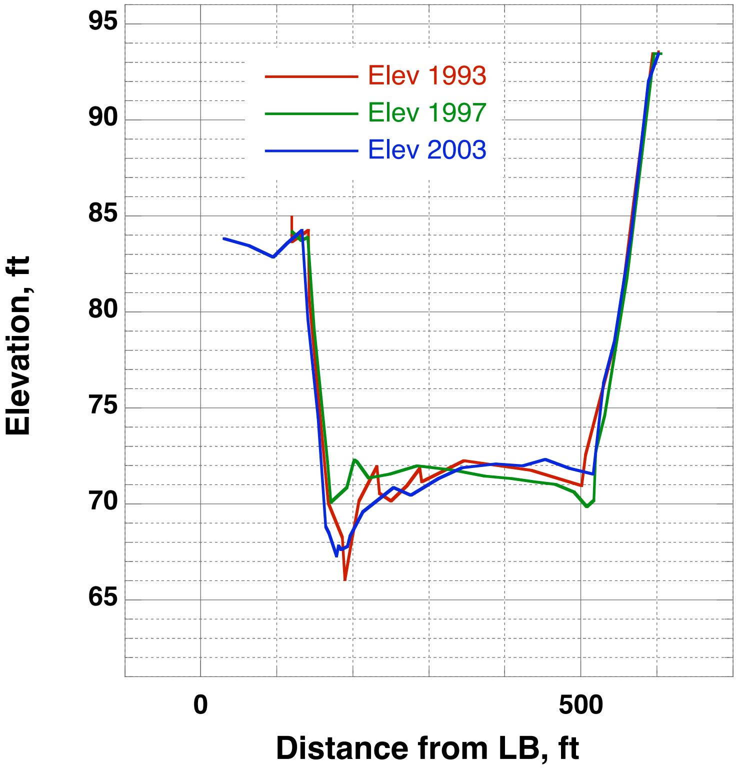

Emmerson Bar XS6+00
100
95
90
85
80
75
70
65
-500
0
500
1000
Distance from LB, ft
Elevation, ft
1994
1997
2003


Emmerson Bar XS1+00


Blue Lake Bar XS Disk 1

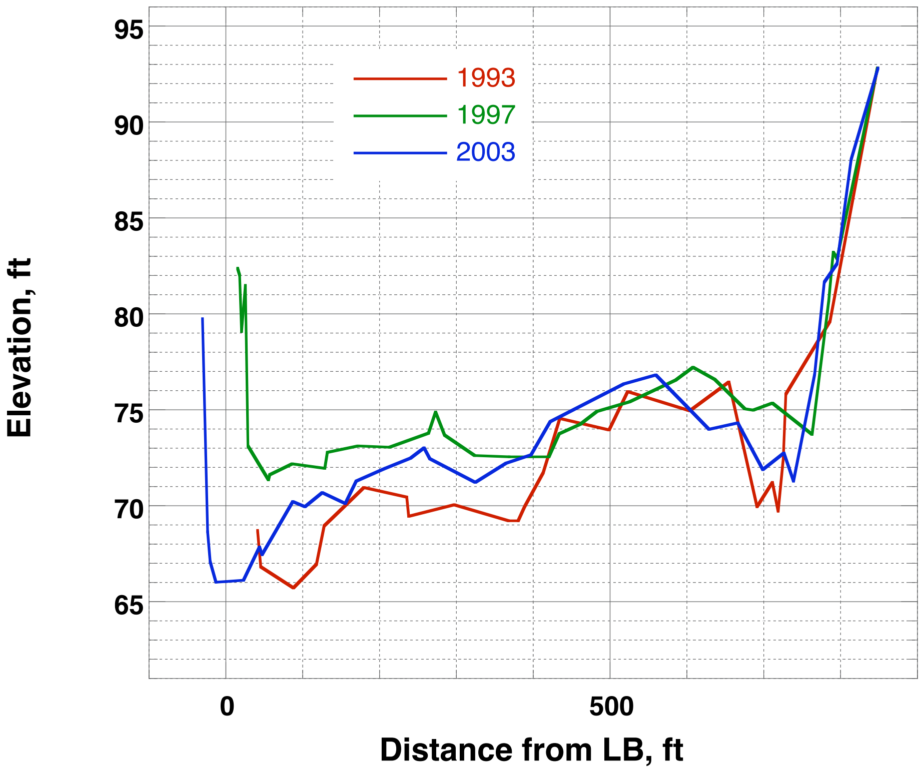


Blue Lake Bar XS Disk 2

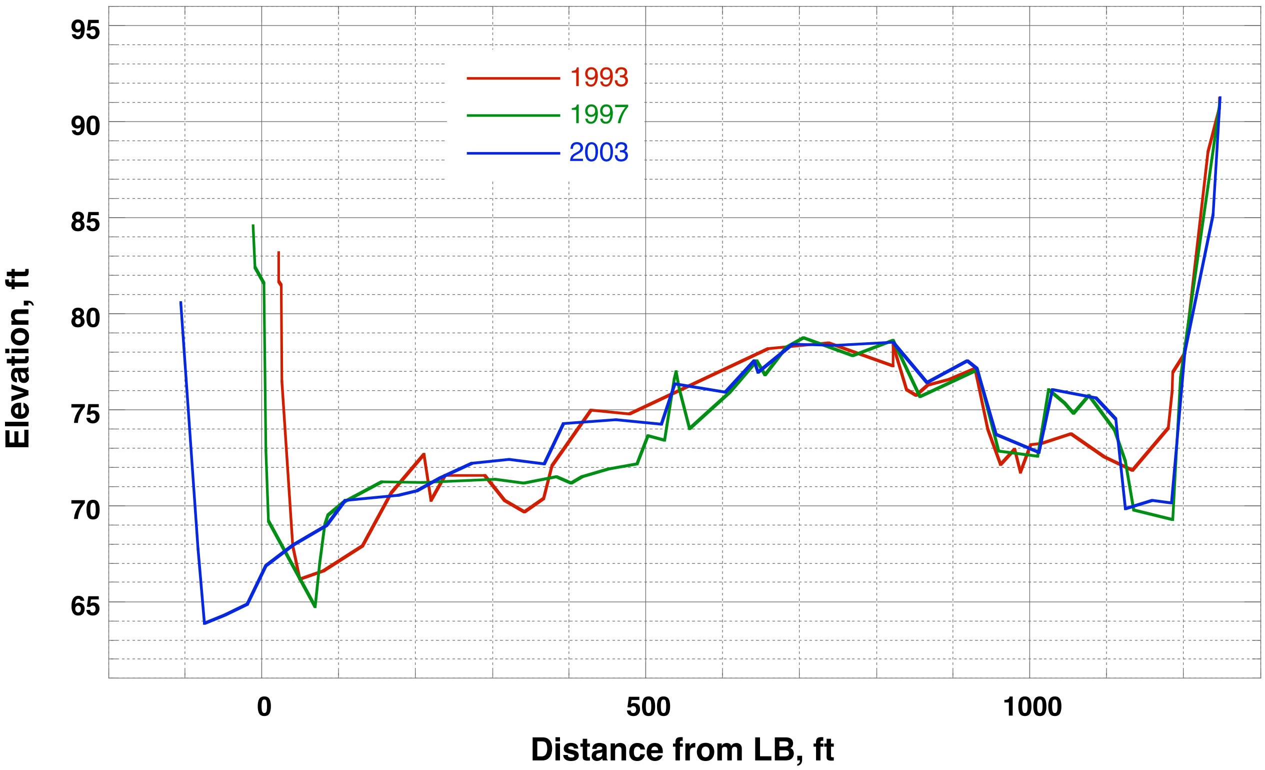


Blue Lake Bar XS 0+00

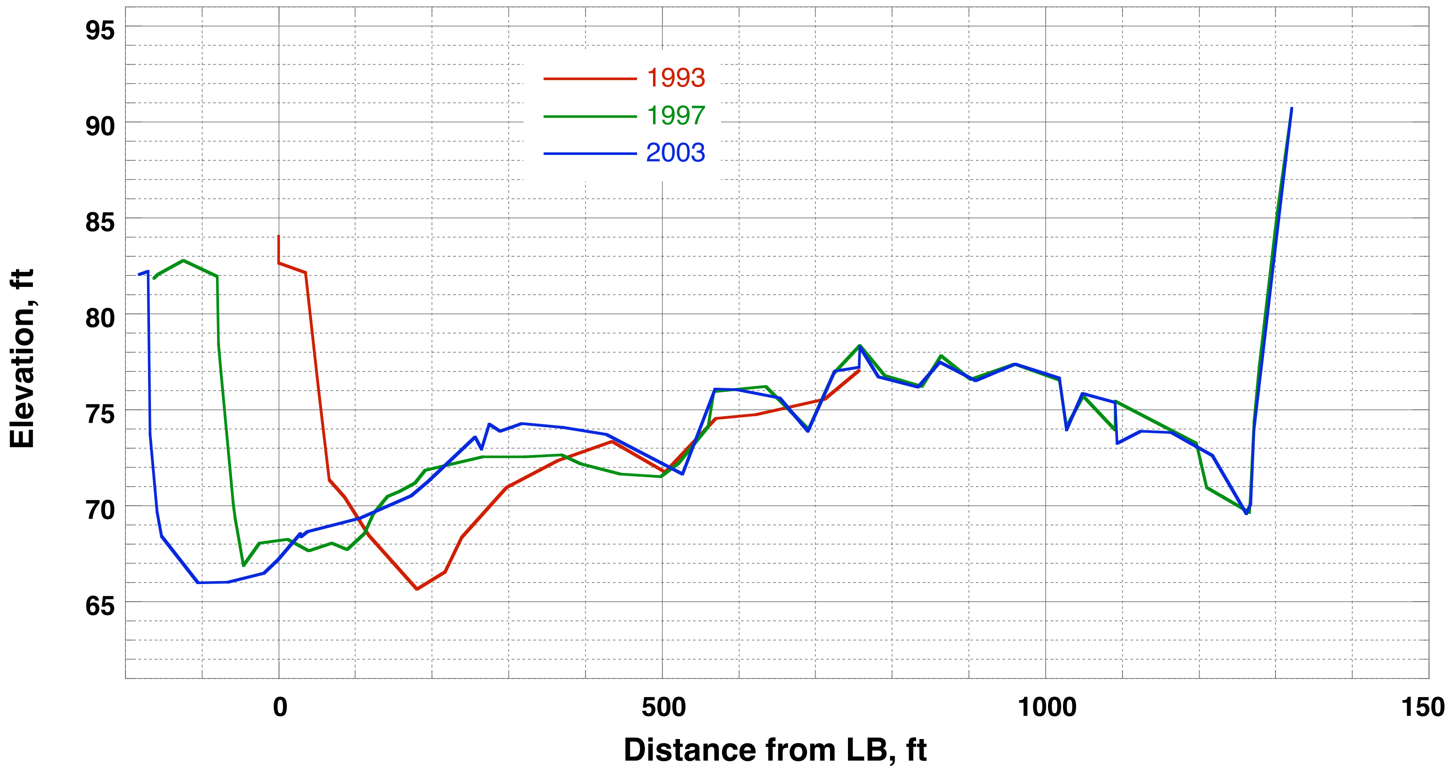
Blue Lake Bar XS 5+00



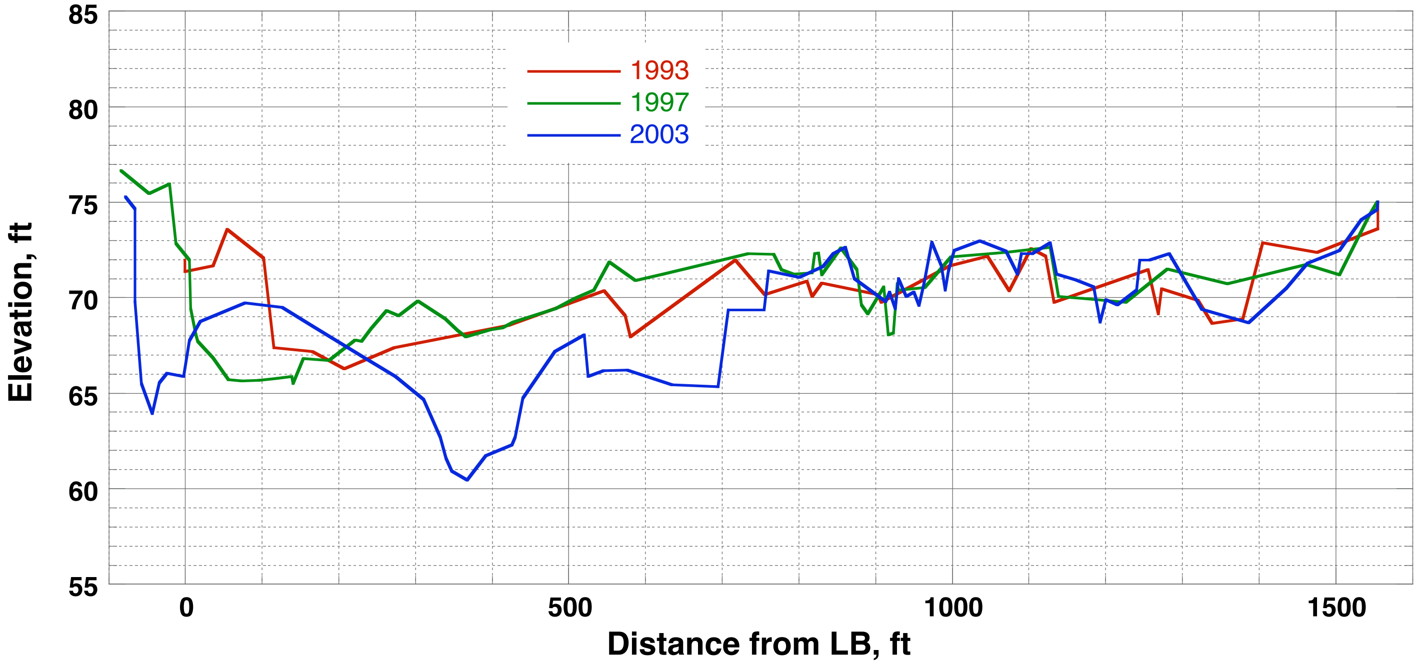
Blue Lake Bar XS 10+00

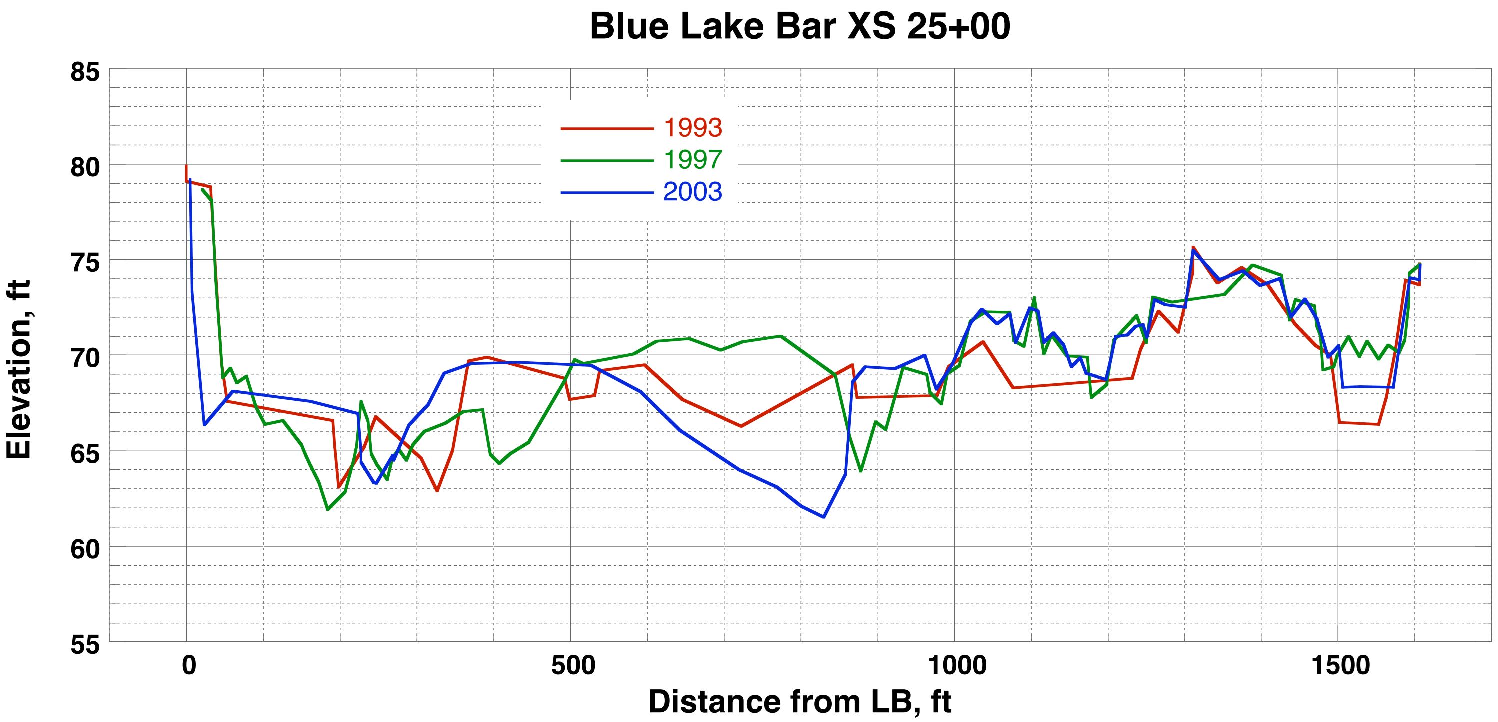


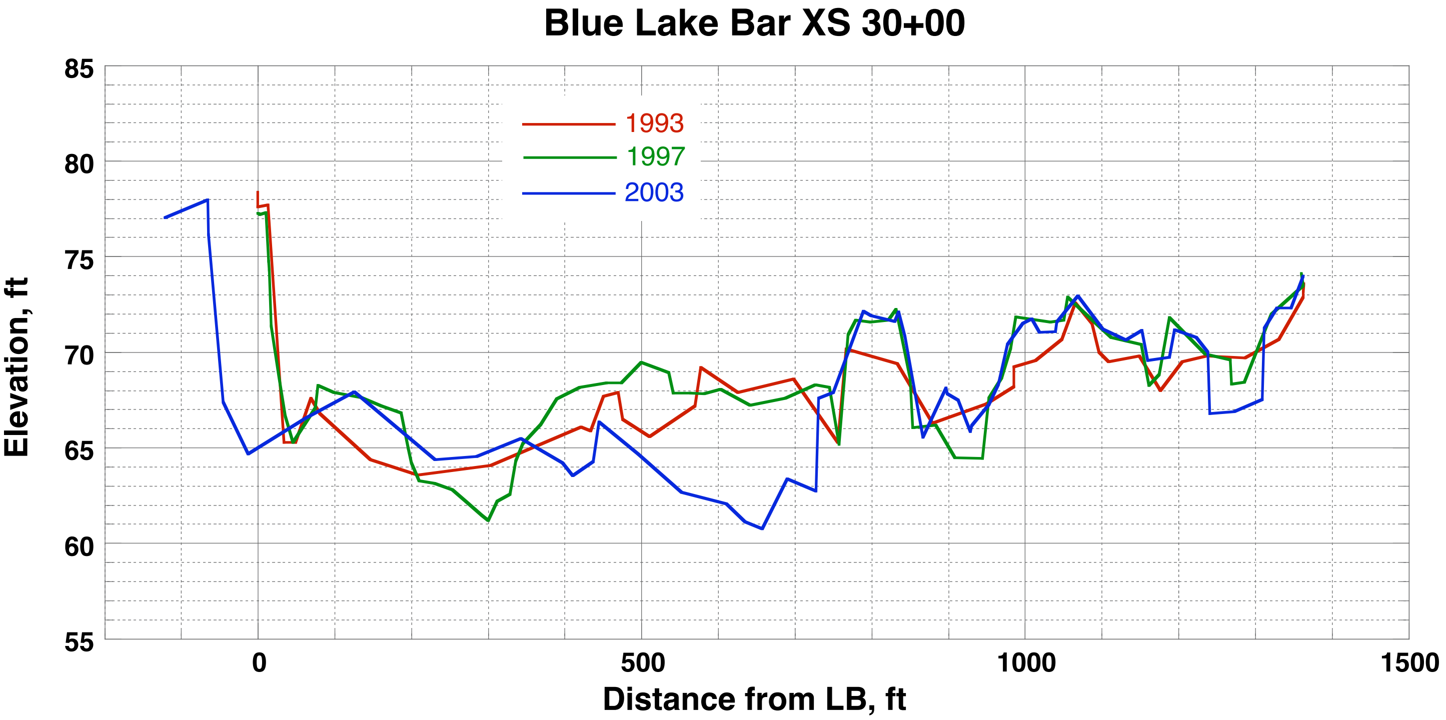
Blue Lake Bar XS 15+00



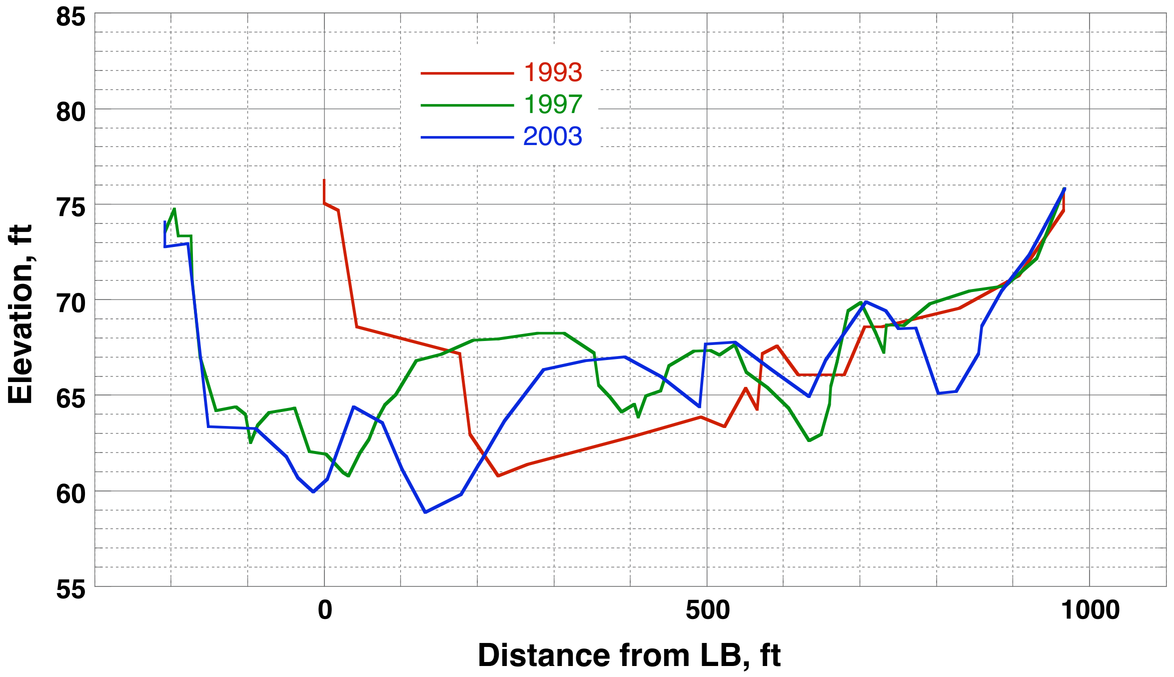
Blue Lake Bar XS 20+00



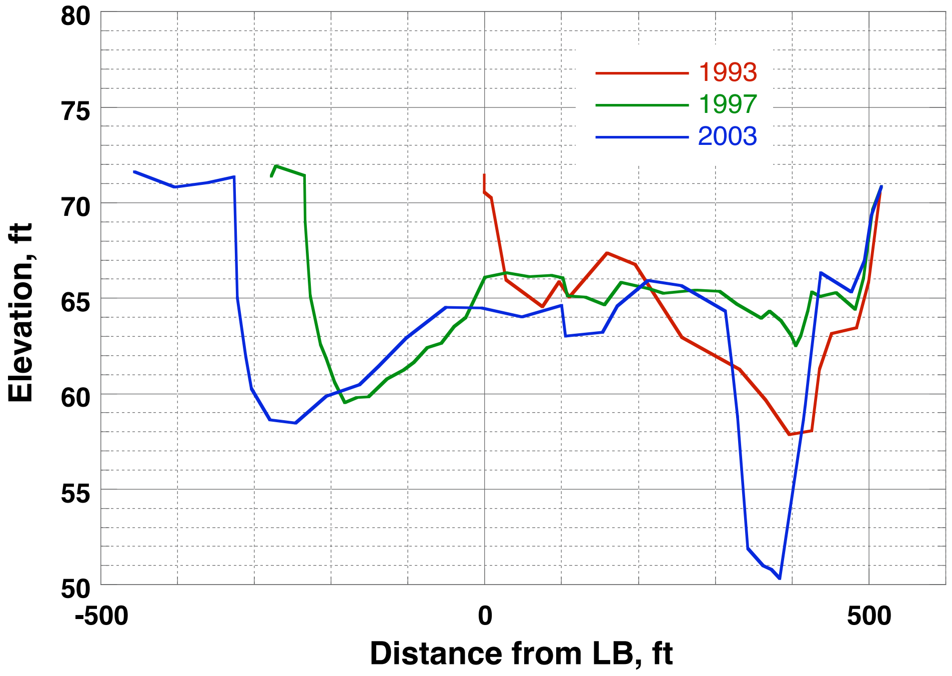

Blue Lake Bar XS 25+00

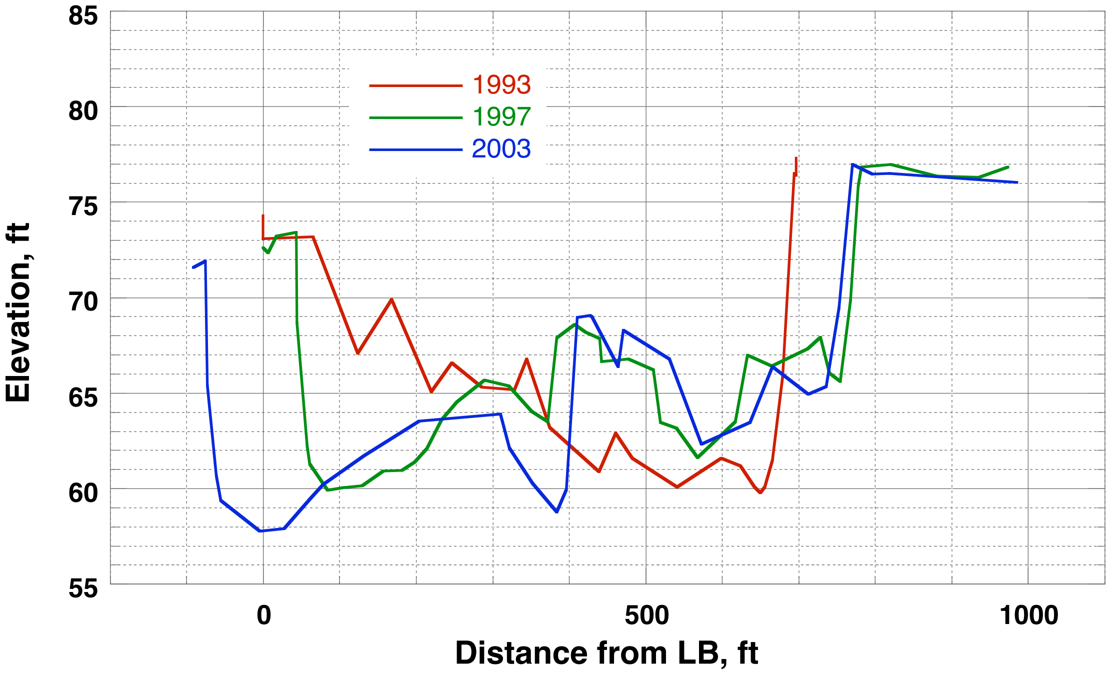

Blue Lake Bar XS 30+00

Blue Lake Bar XS 34+00

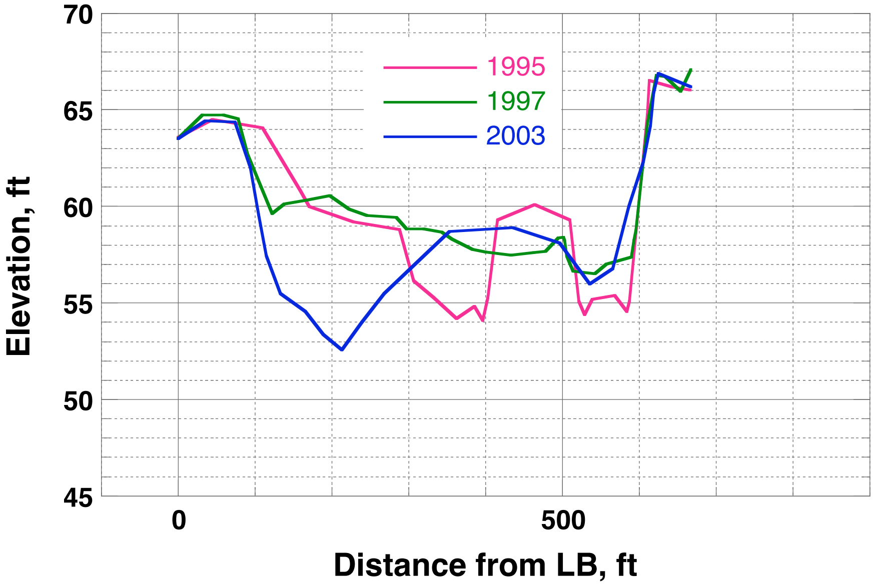


Blue Lake Bar XS 38+00

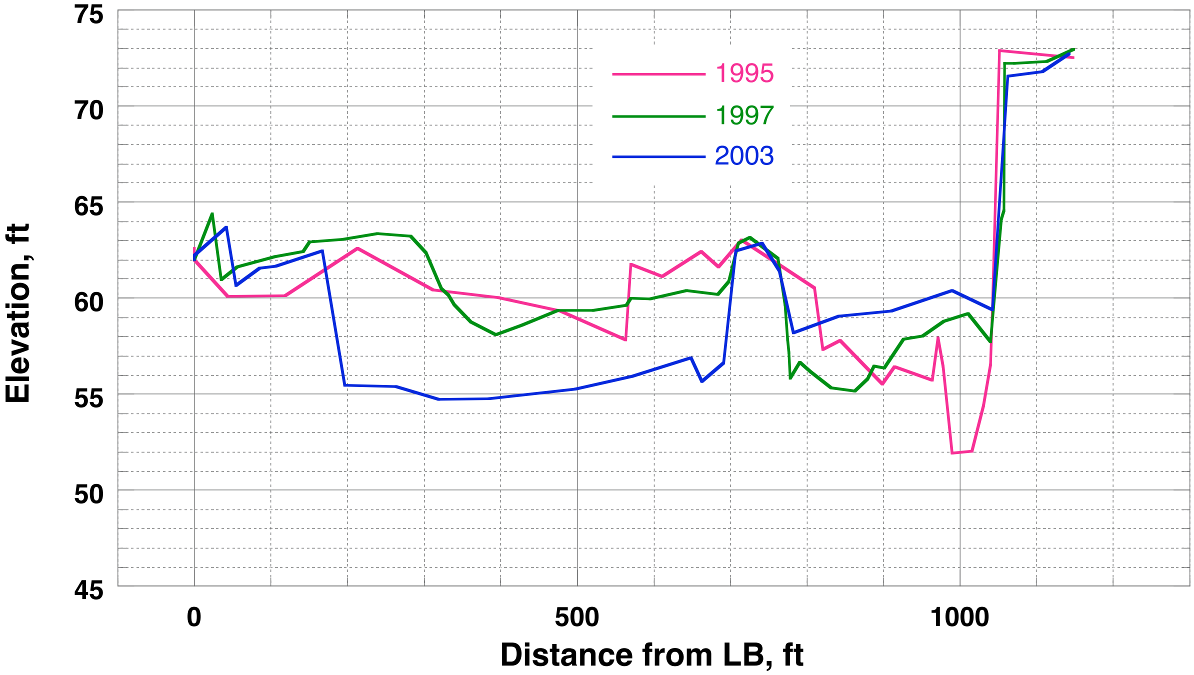


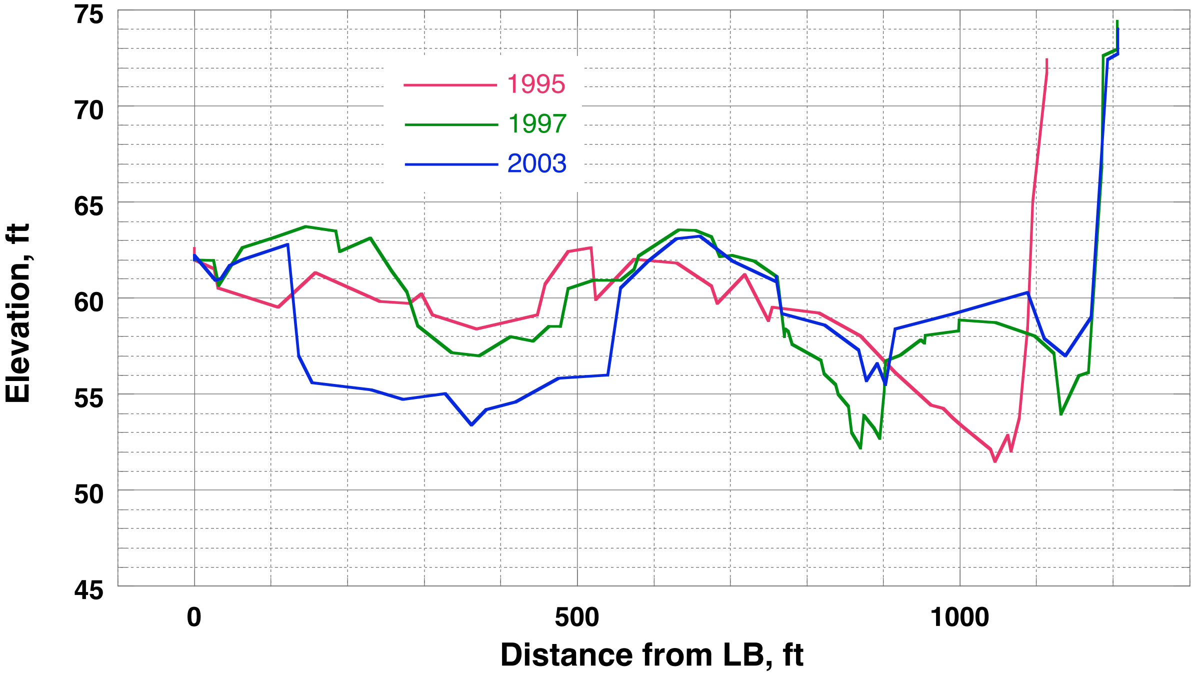


Blue Lake Bar XS 42+00

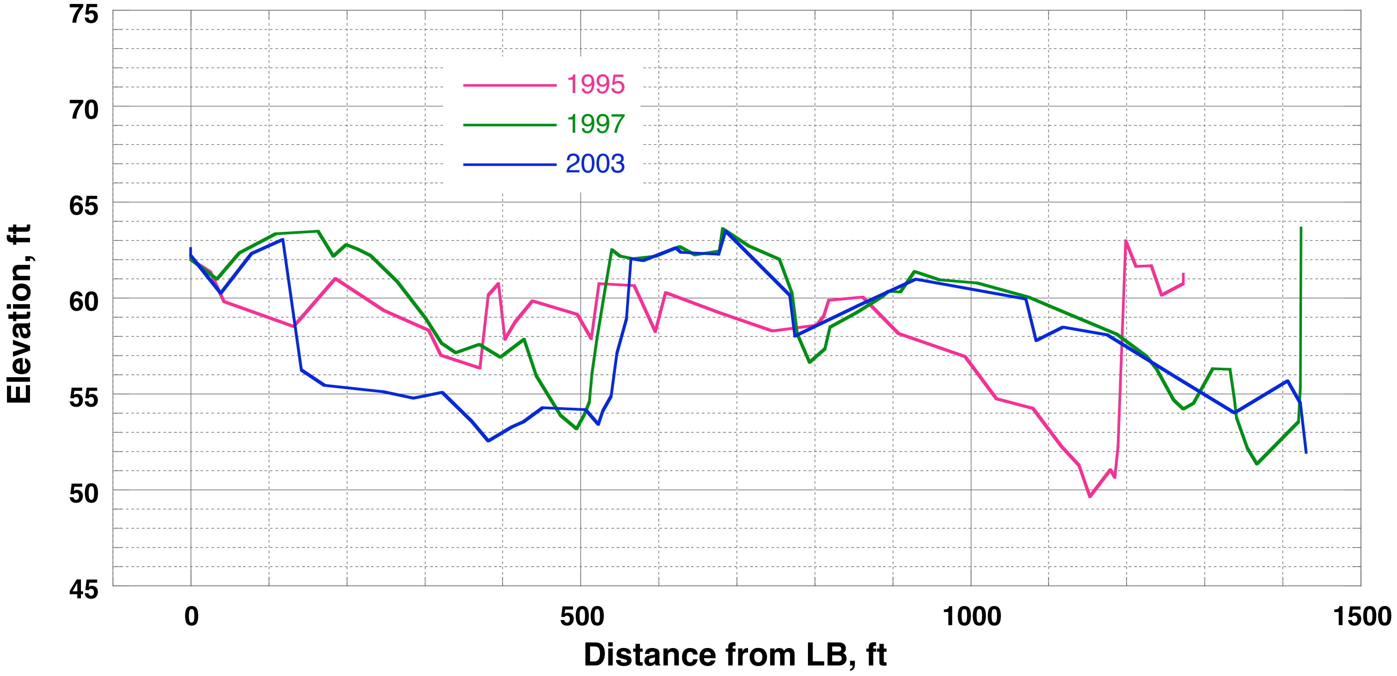


Christie Bar XS CH-1 (Section 5)

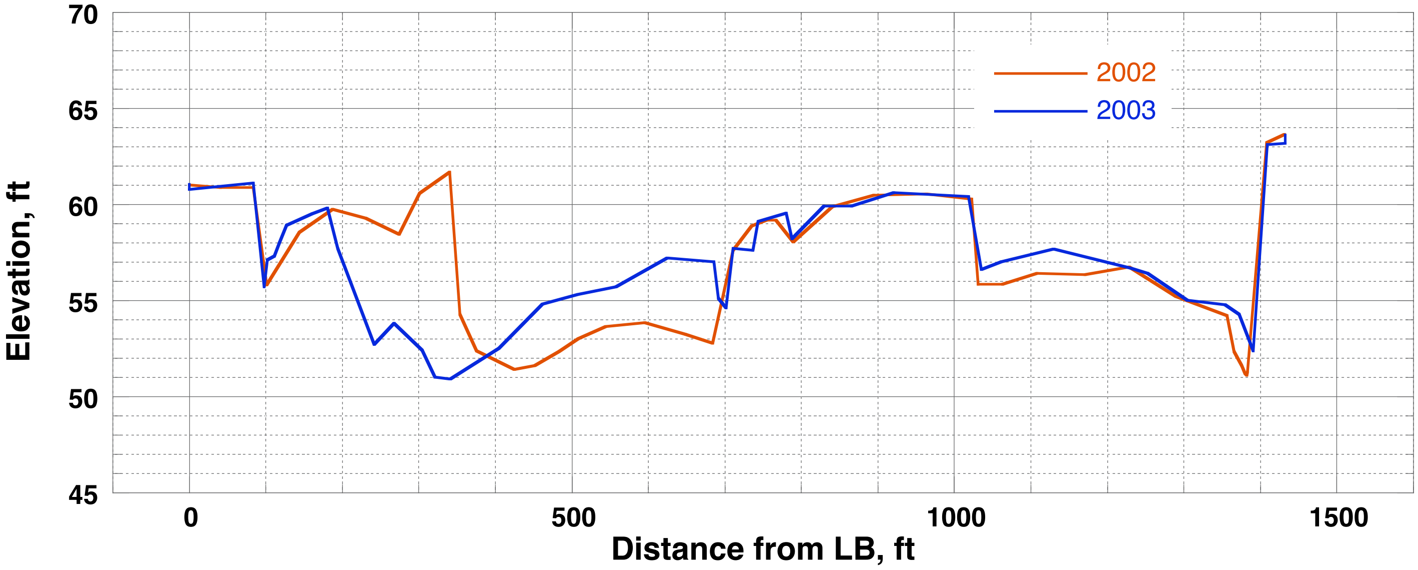

Christie Bar XS Radial 4


Christie Bar XS CH-2 (Radial 3)

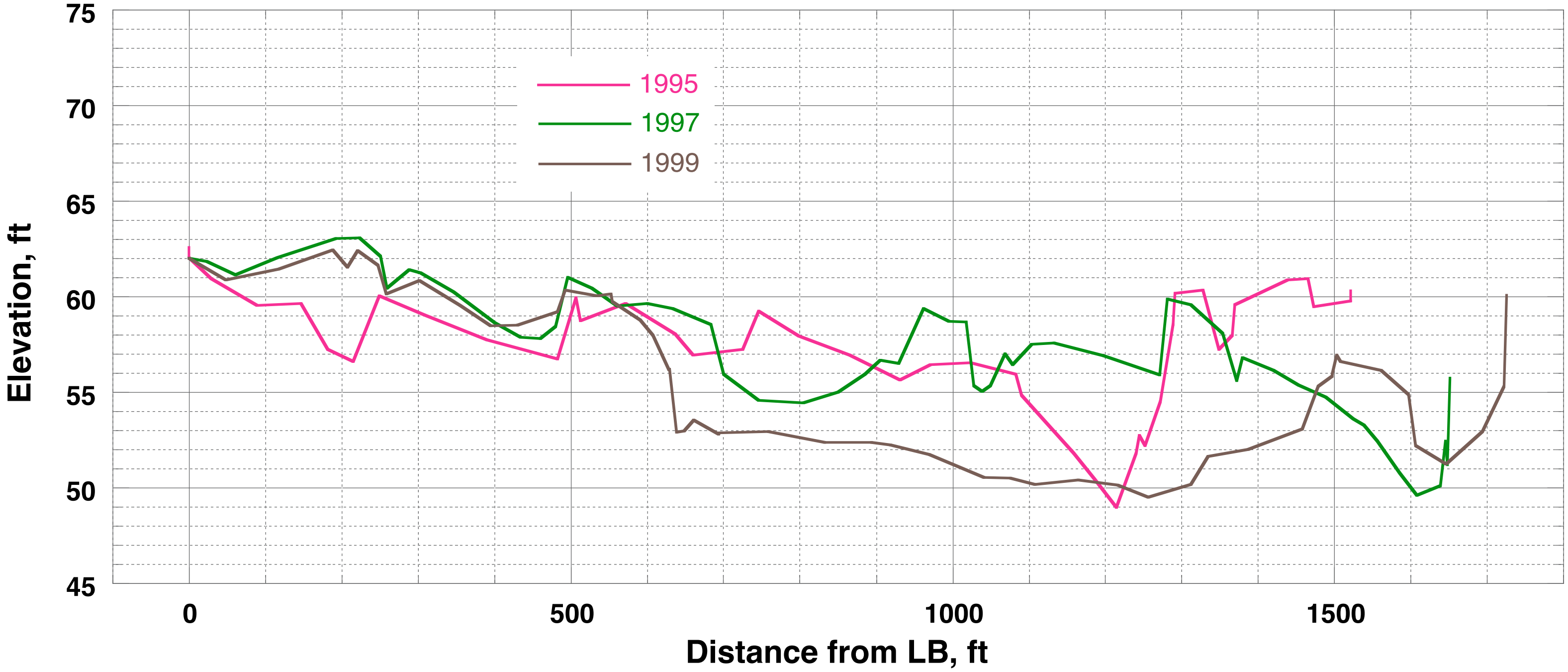
Christie Bar XS Radial 2



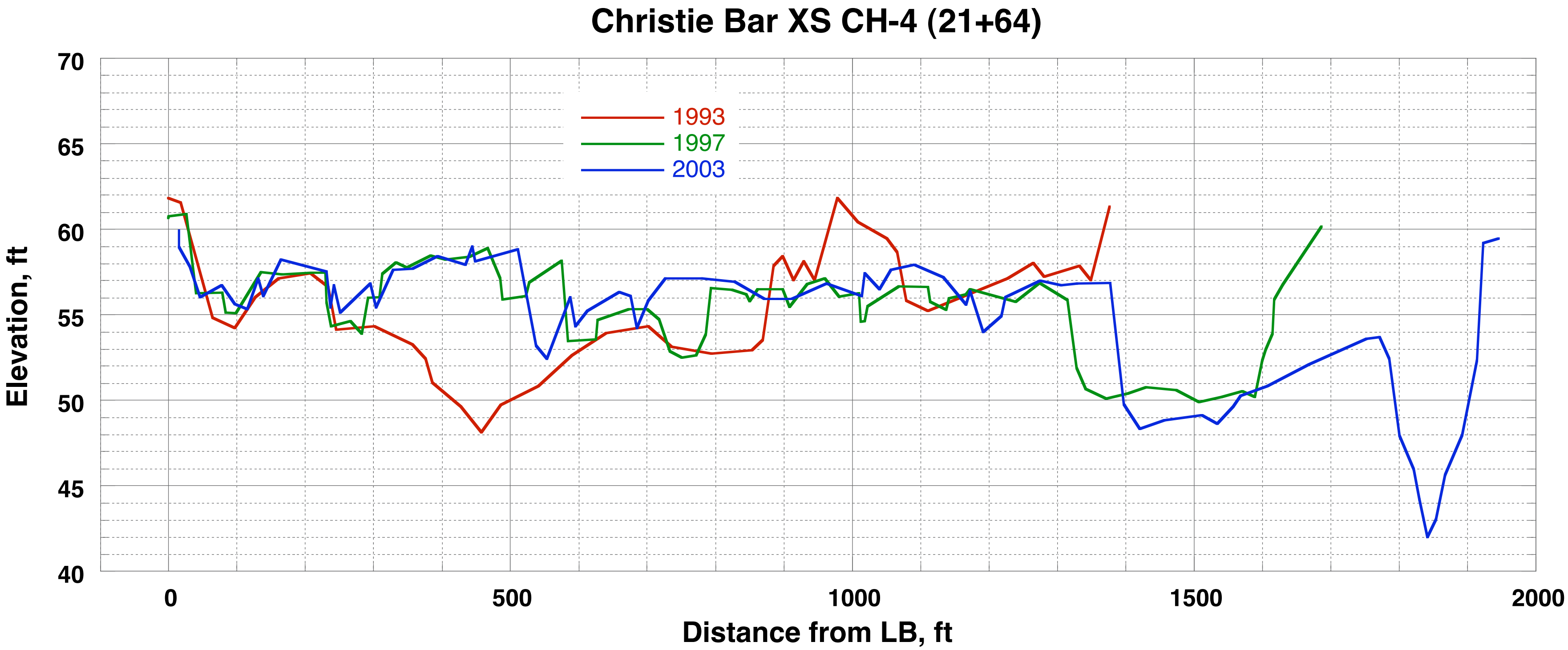
Christie Bar XS CH-3

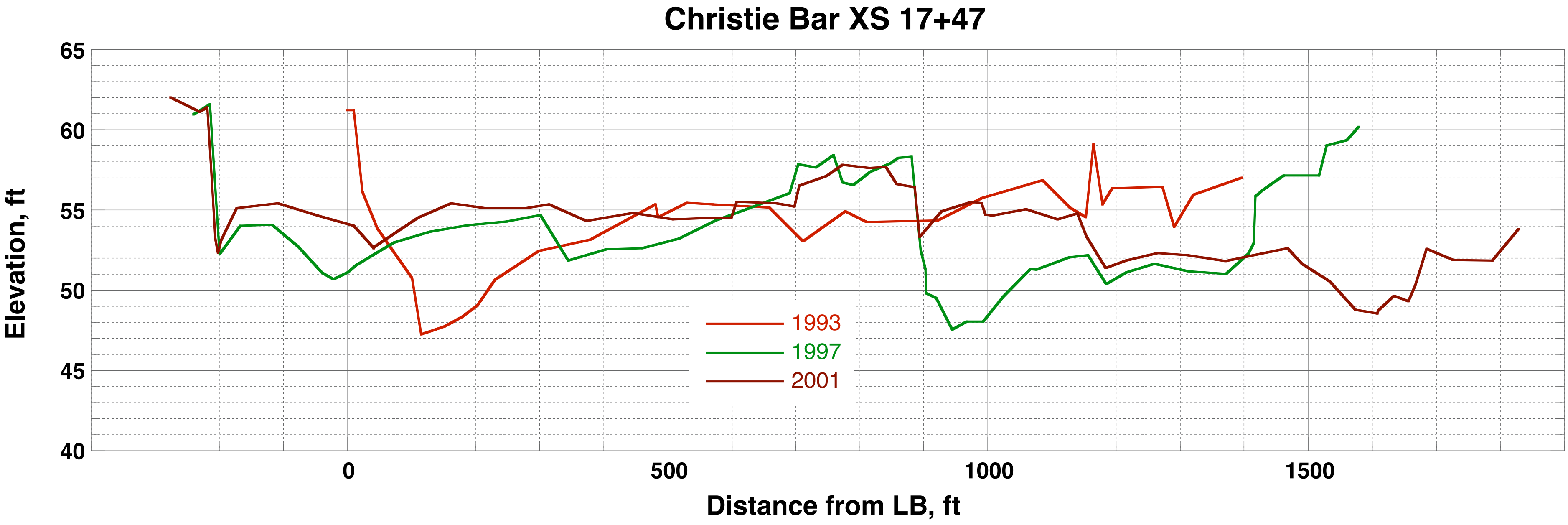


Christie Bar XS Radial 1

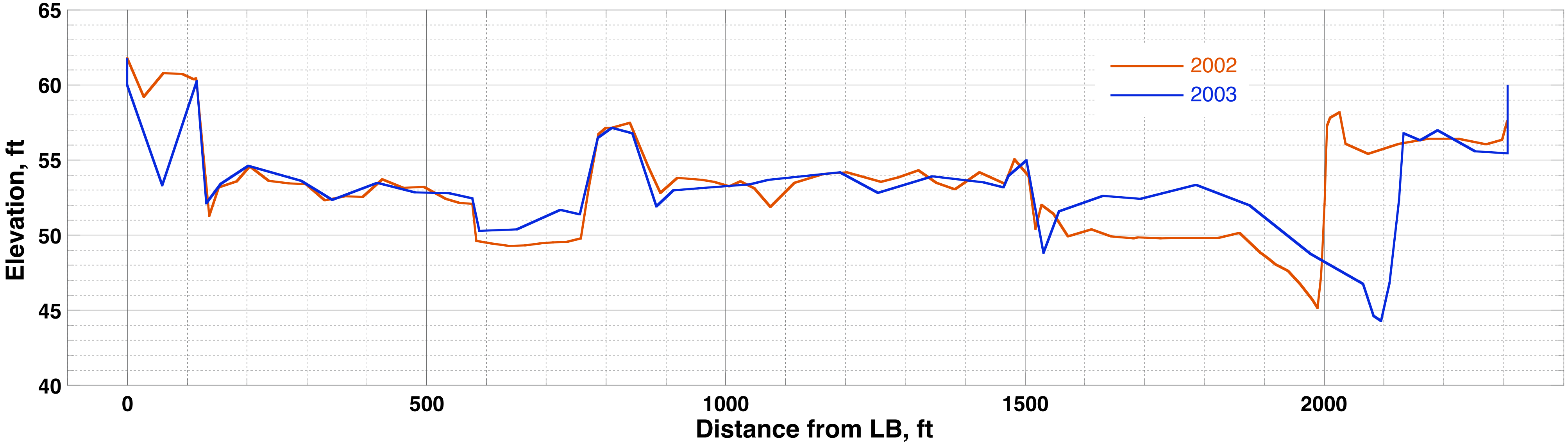


Christie Bar XS 22+87

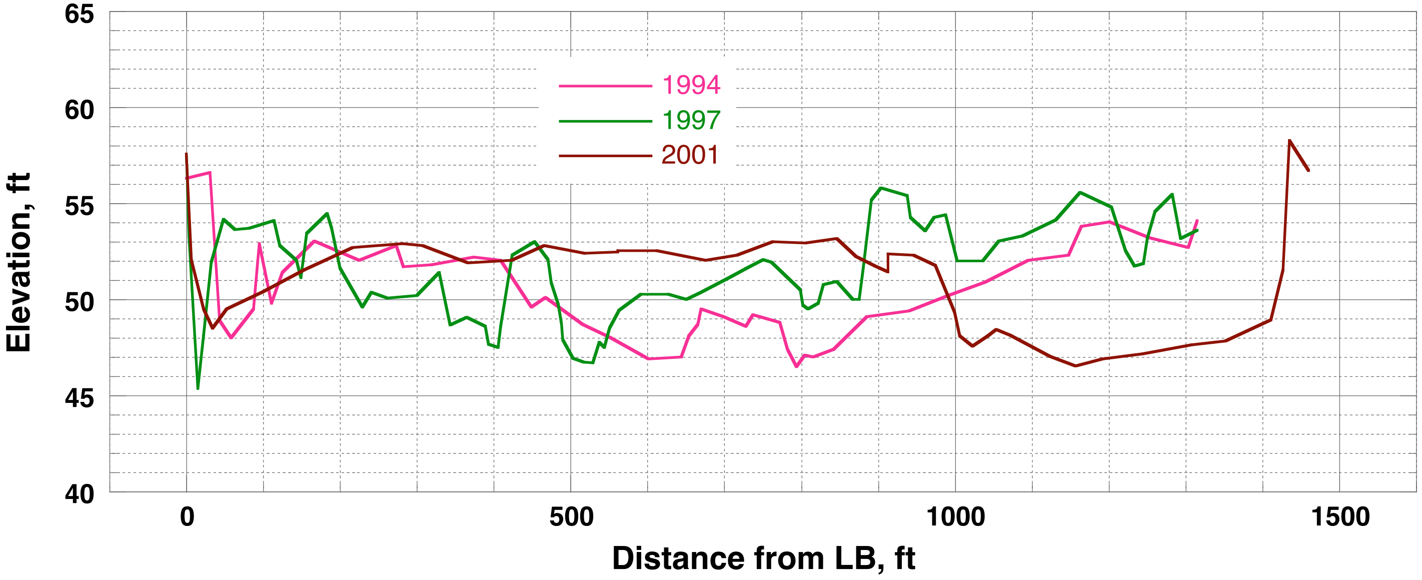

Christie Bar XS CH-4 (21+64)


Christie Bar XS 17+47

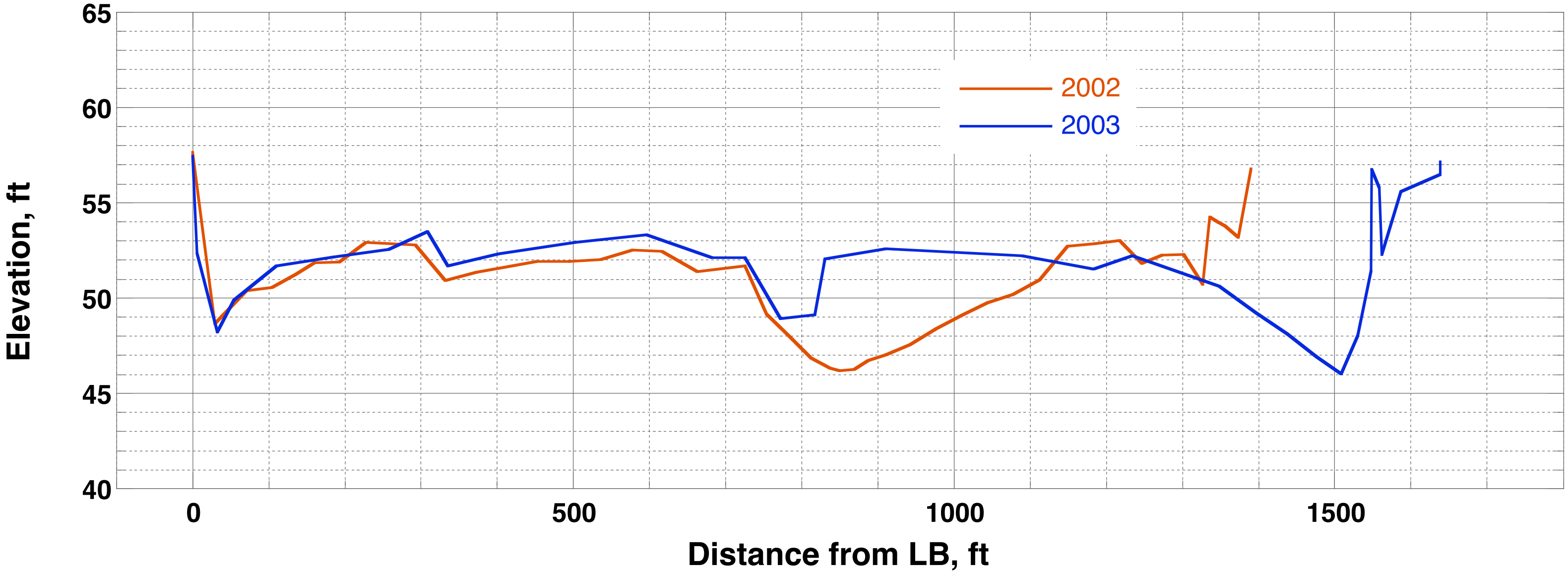
Christie Bar XS CH-5



Christie Bar XS 13+33

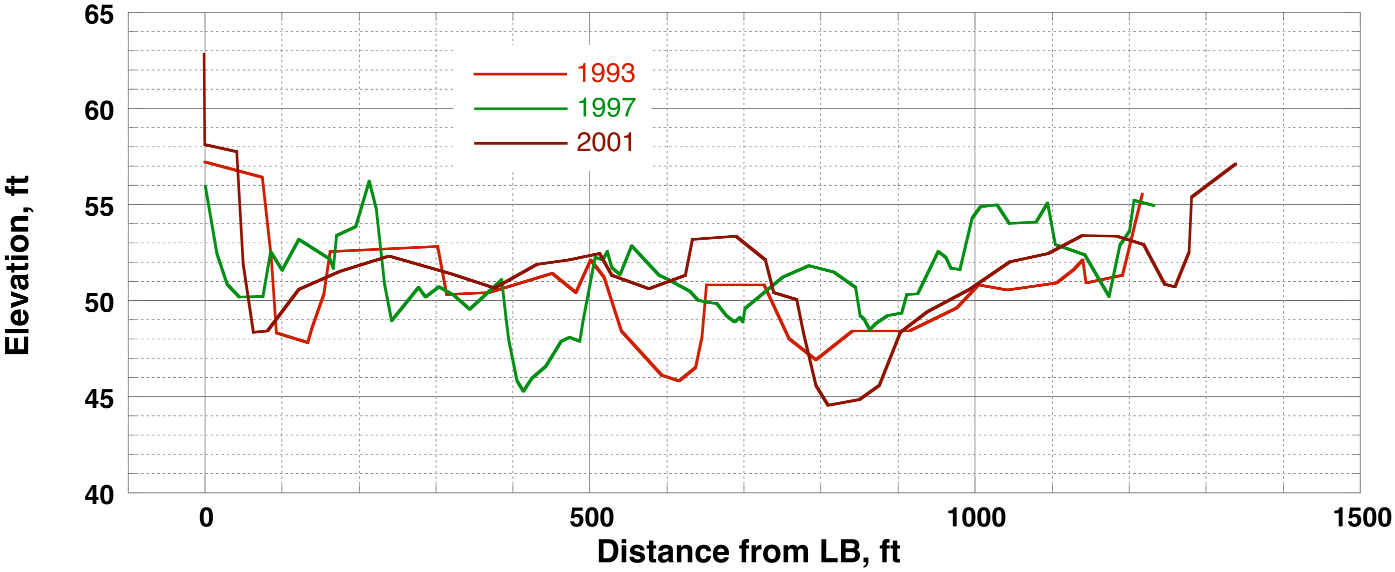


Christie Bar XS 9+99

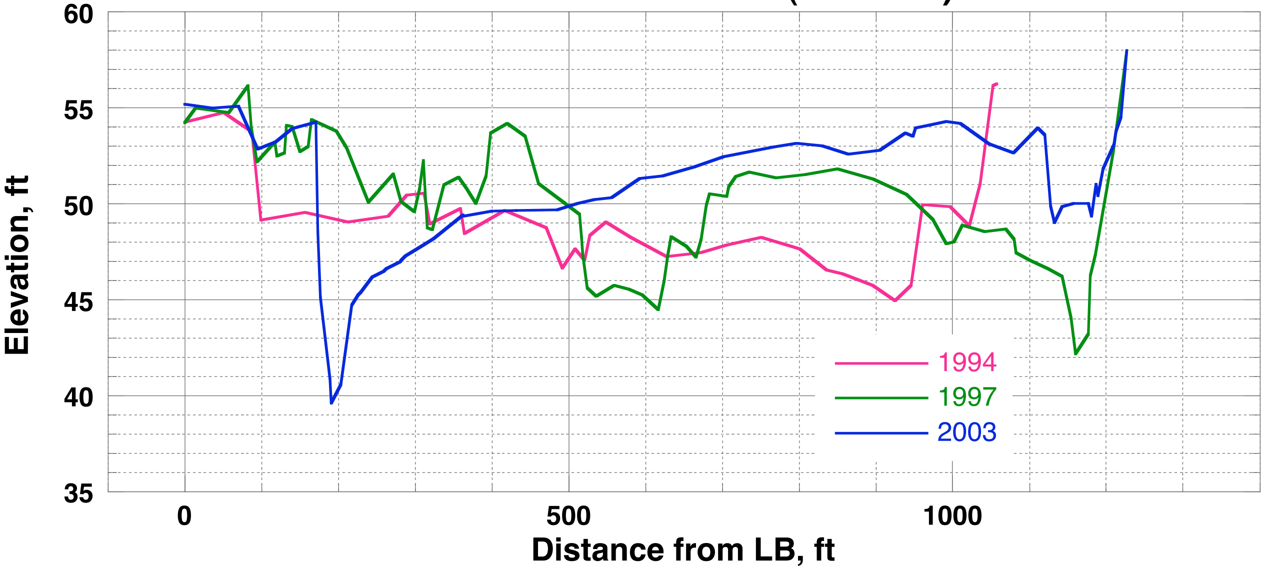


Christie Bar XS CH-6

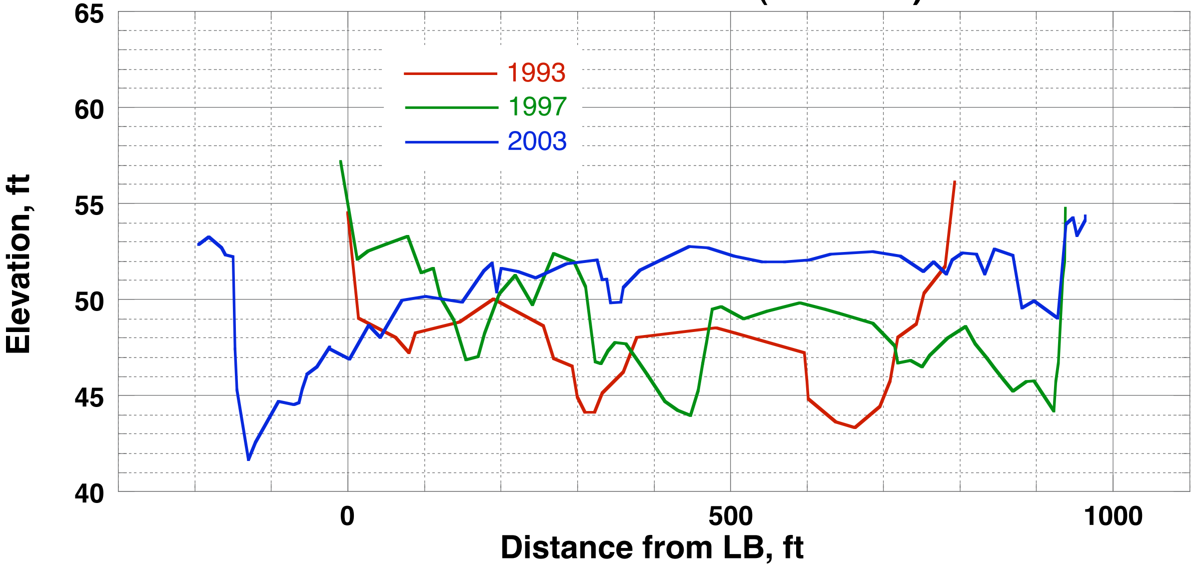
Christie Bar XS 6+66

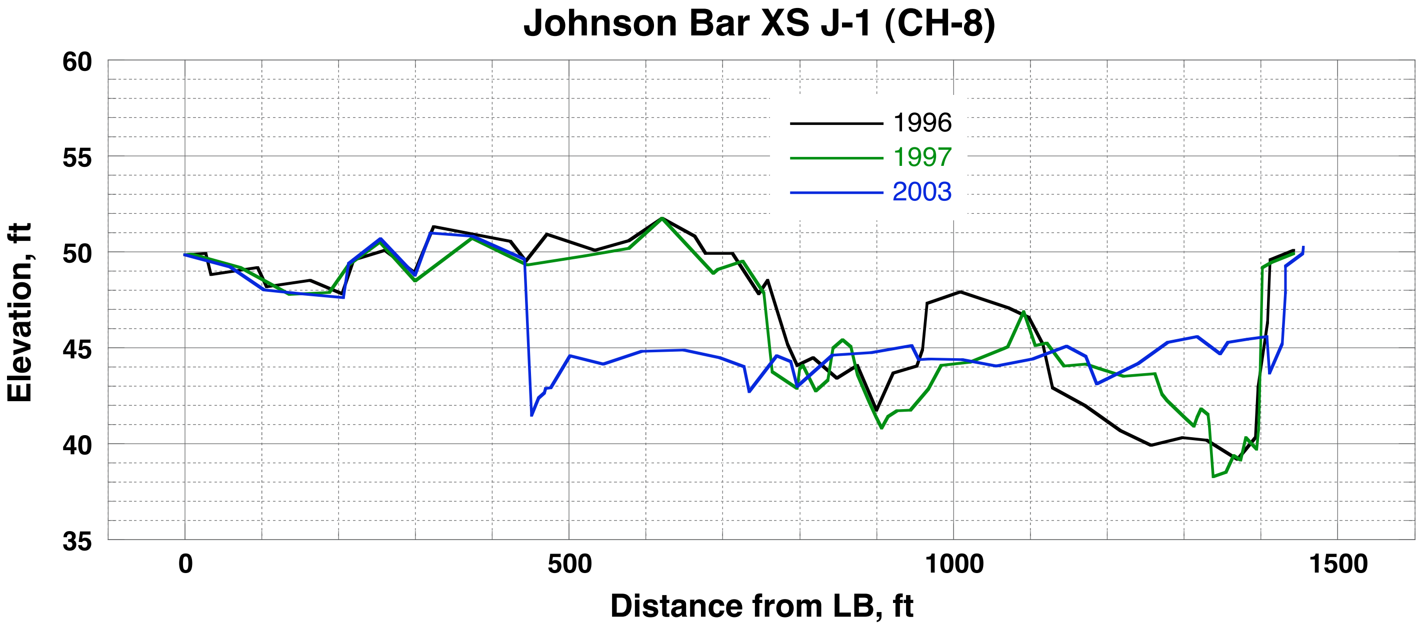


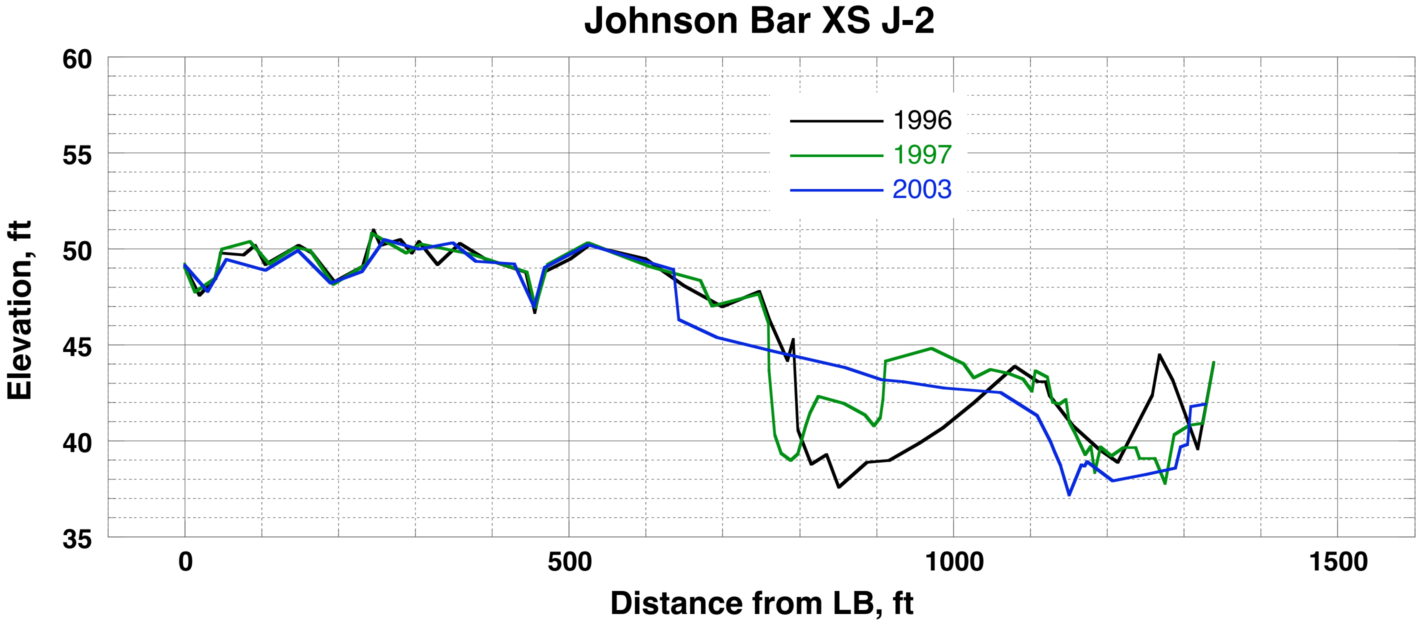
Christie Bar XS CH-7 (XS 3+33)

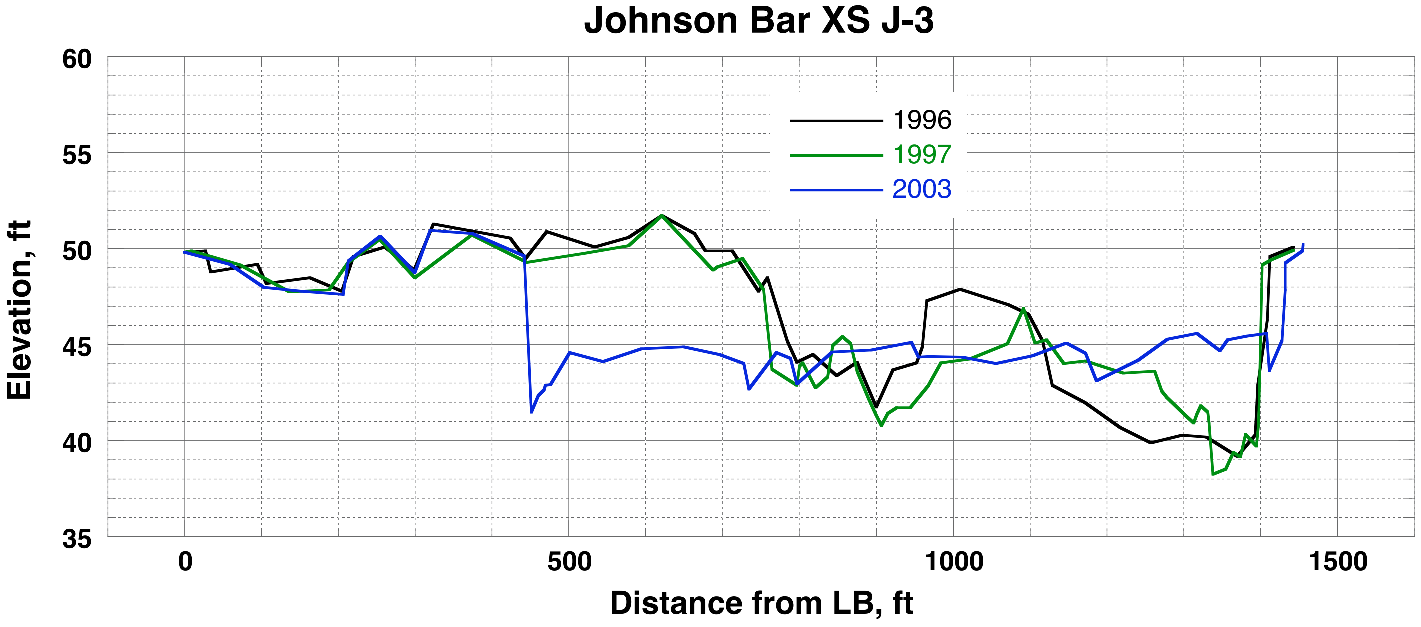


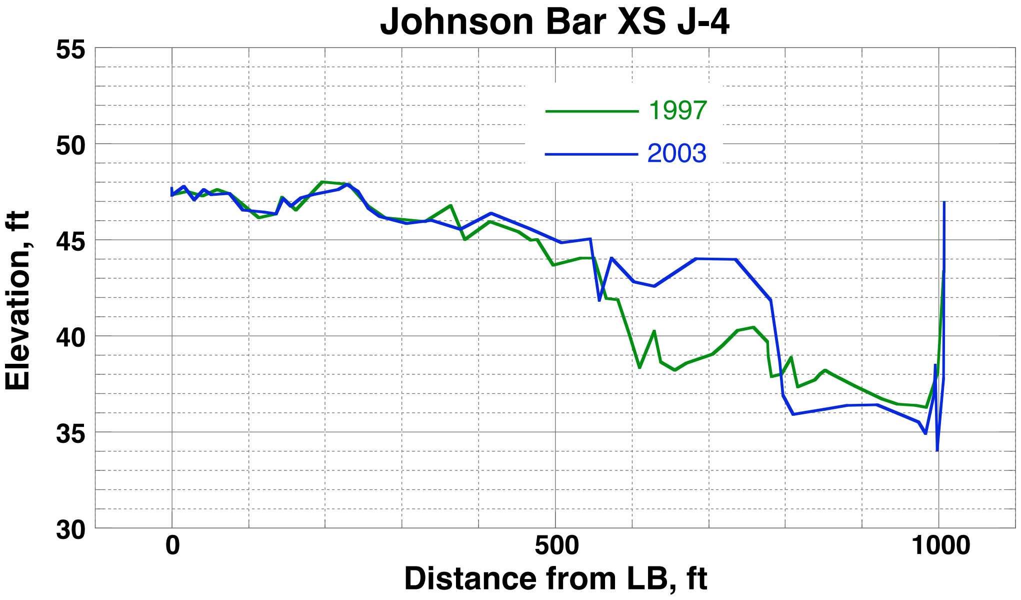
Christie Bar XS CH-8 (XS 0+00)

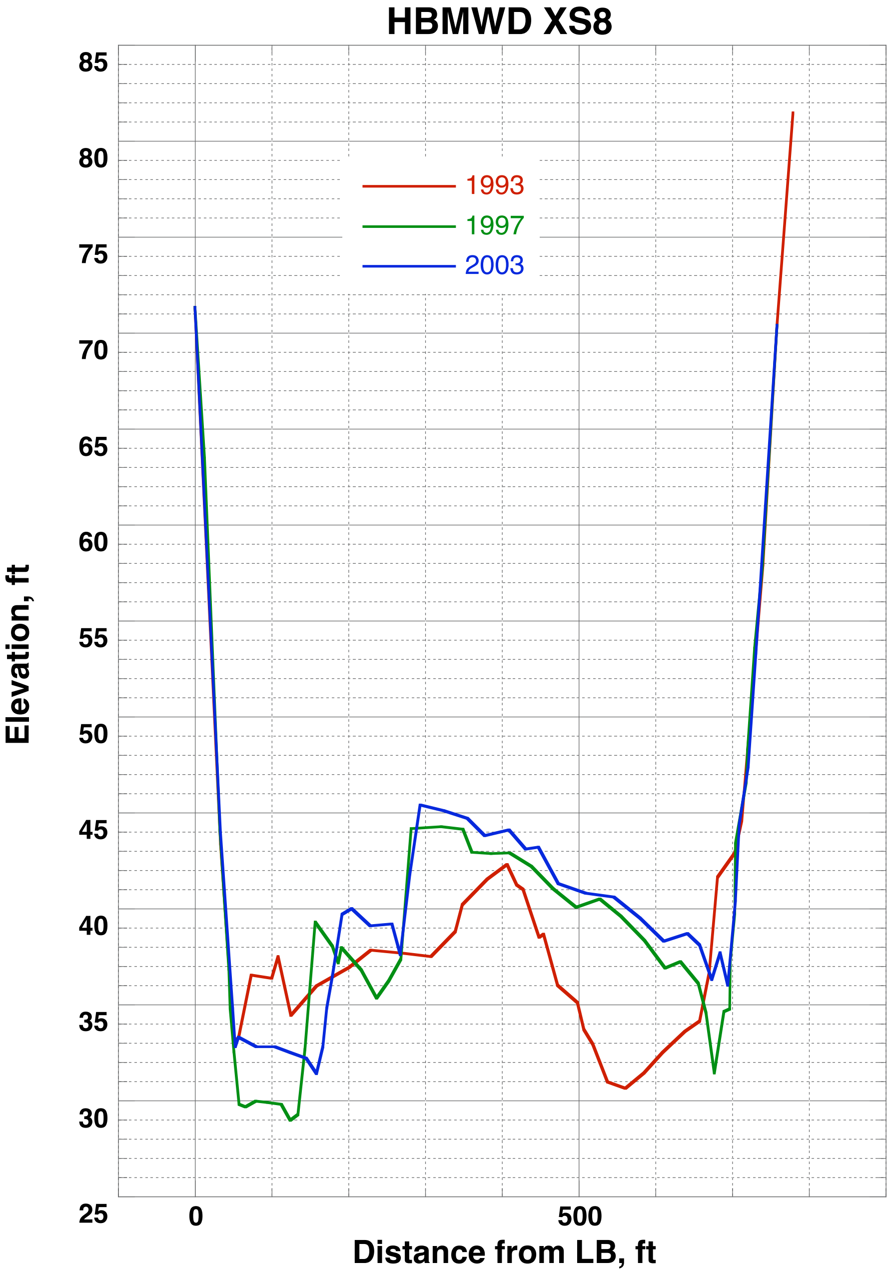


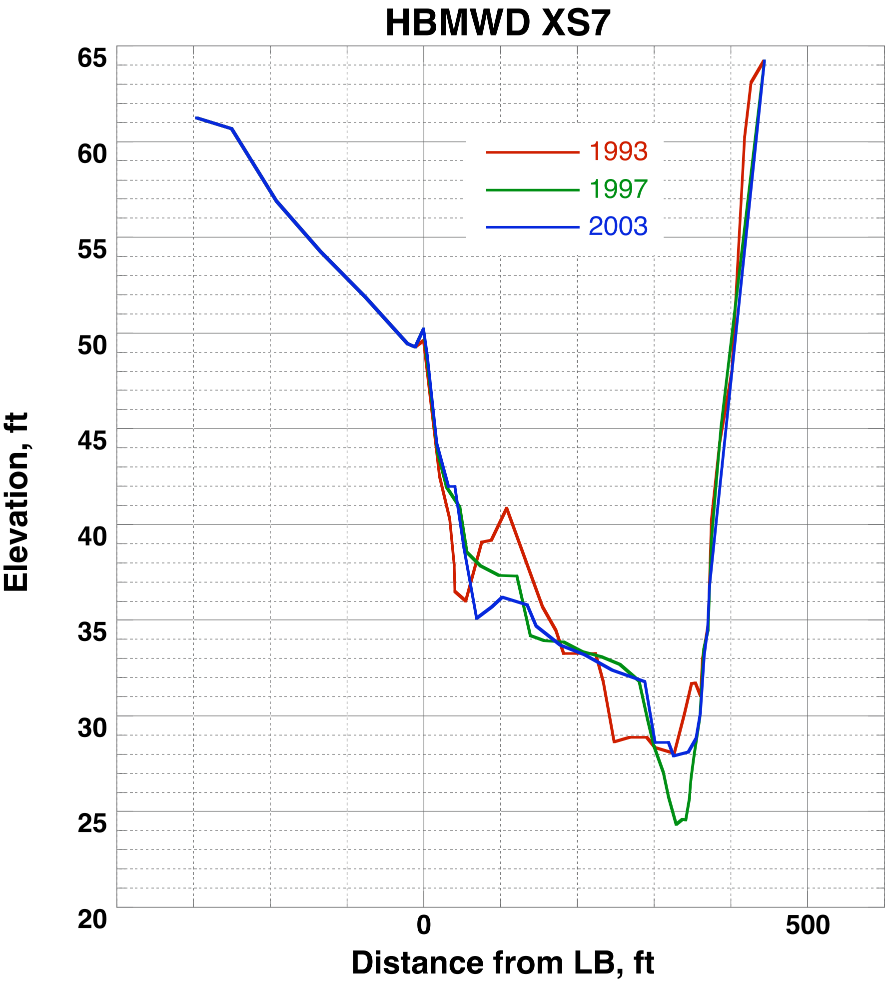

Johnson Bar XS J-1 (CH-8)

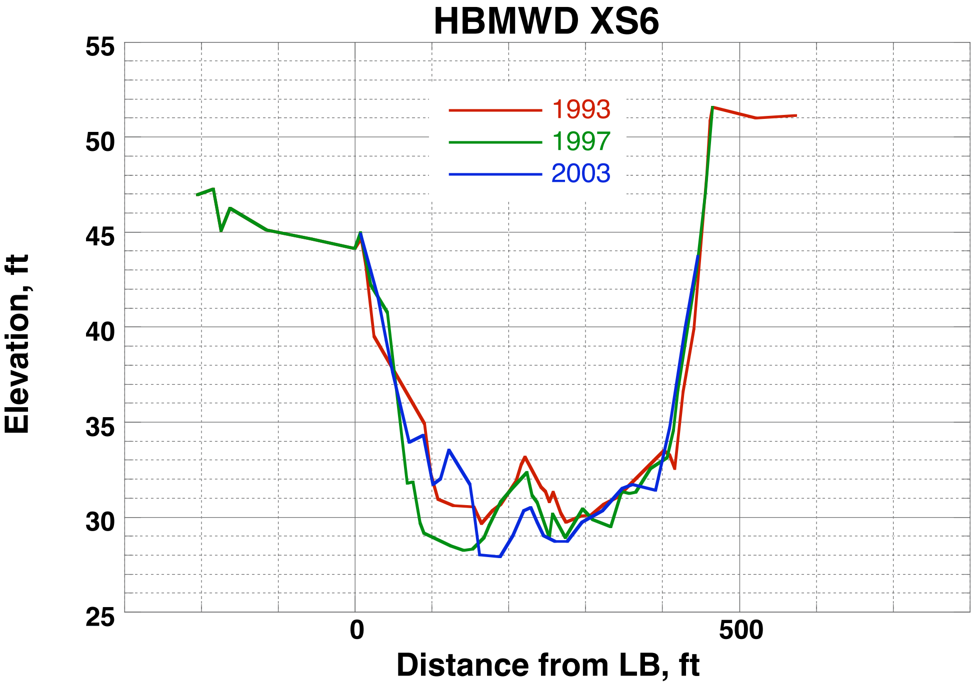

Johnson Bar XS J-2

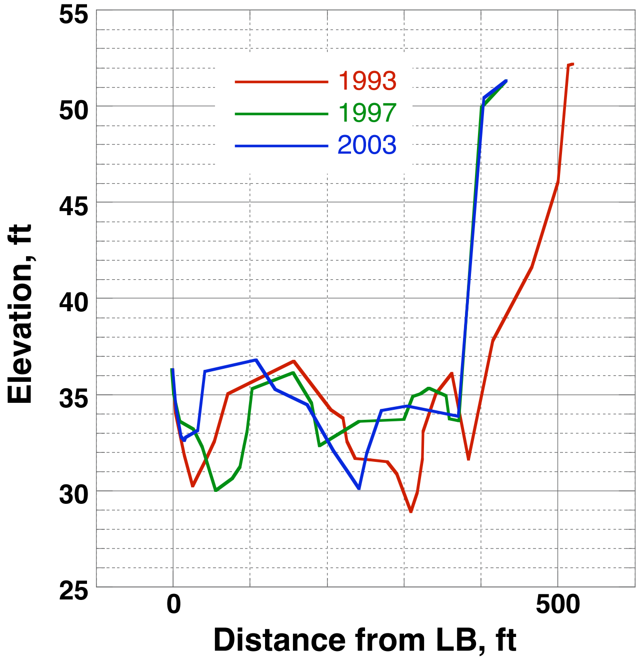

Johnson Bar XS J-3


Johnson Bar XS J-4
1997
2003
Elevation, ft
55
50
45
40
35
30
0
500
1000
Distance from LB, ft

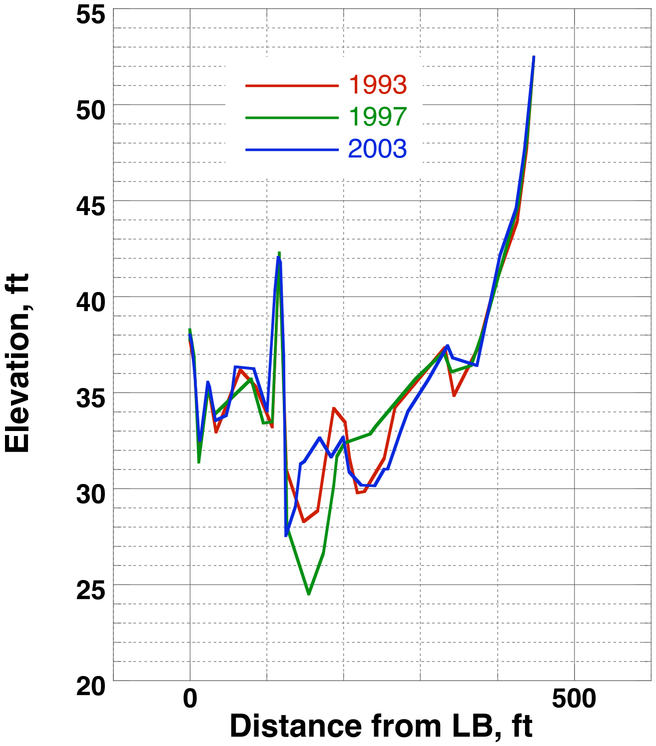

HBMWD XS8
1993
1997
2003
Elevation, ft
85
80
75
70
65
60
55
50
45
40
35
30
25
0
500
Distance from LB, ft


HBMWD XS7
65
60
55
50
45
40
35
30
25
20
Elevation, ft
0
500
Distance from LB, ft
1993
1997
2003


HBMWD XS6
55
50
45
40
35
30
25
Elevation, ft
0
500
Distance from LB, ft
1993
1997
2003

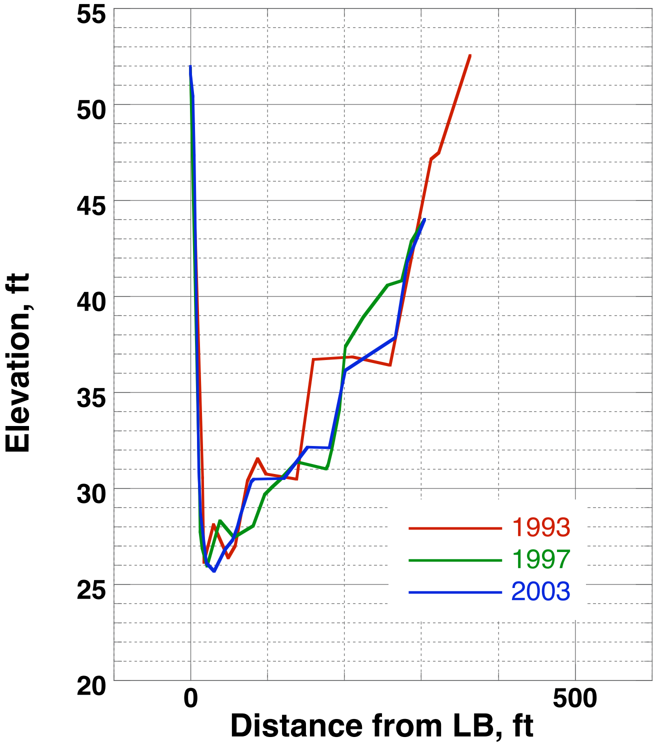


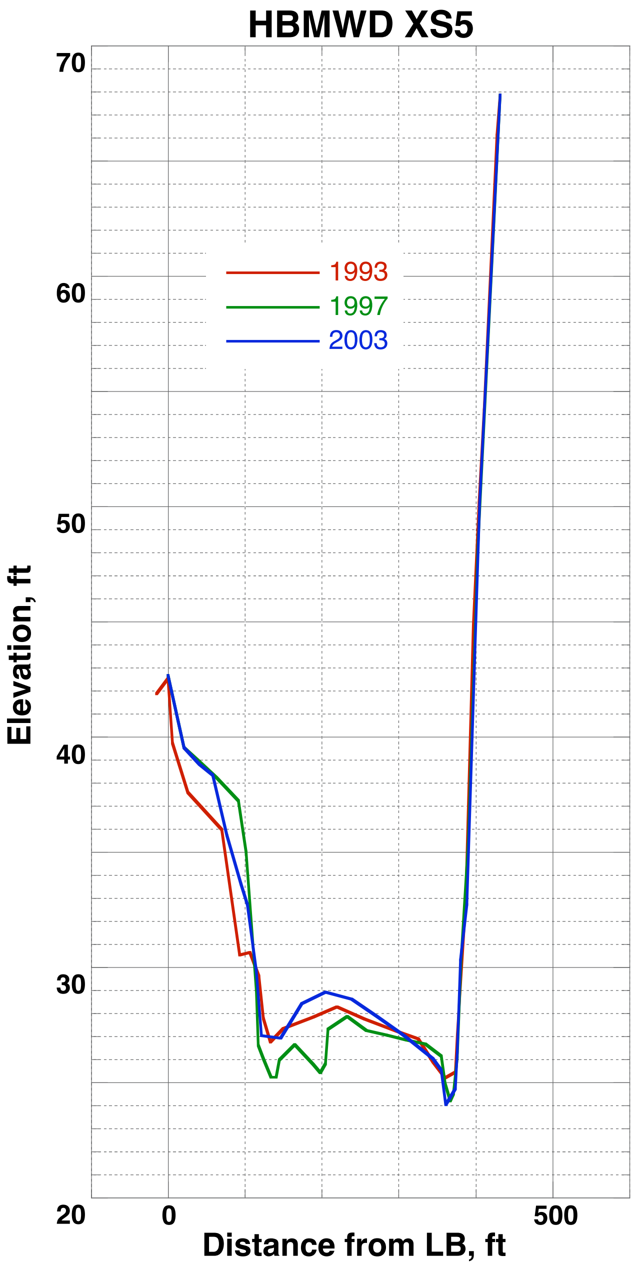
Essex Bar XS1

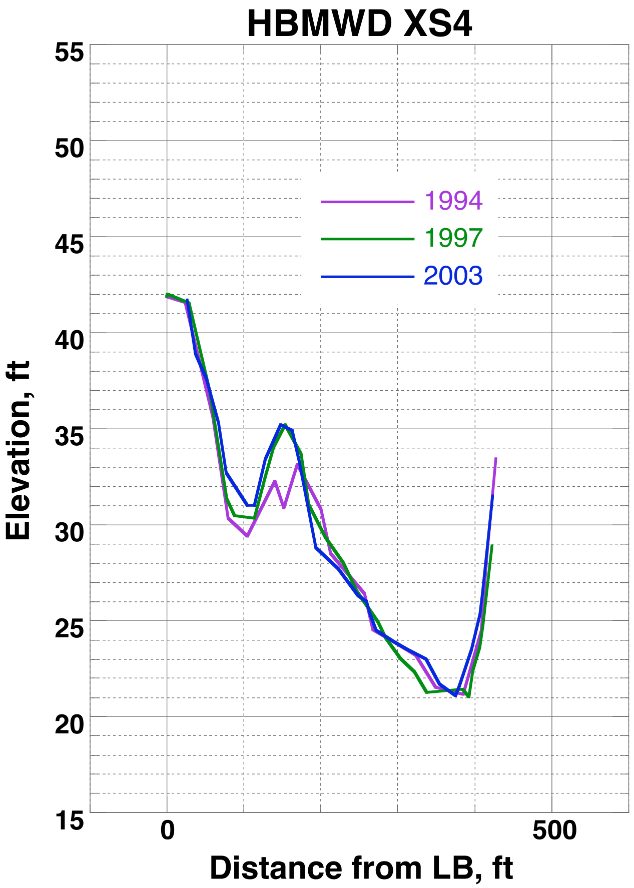


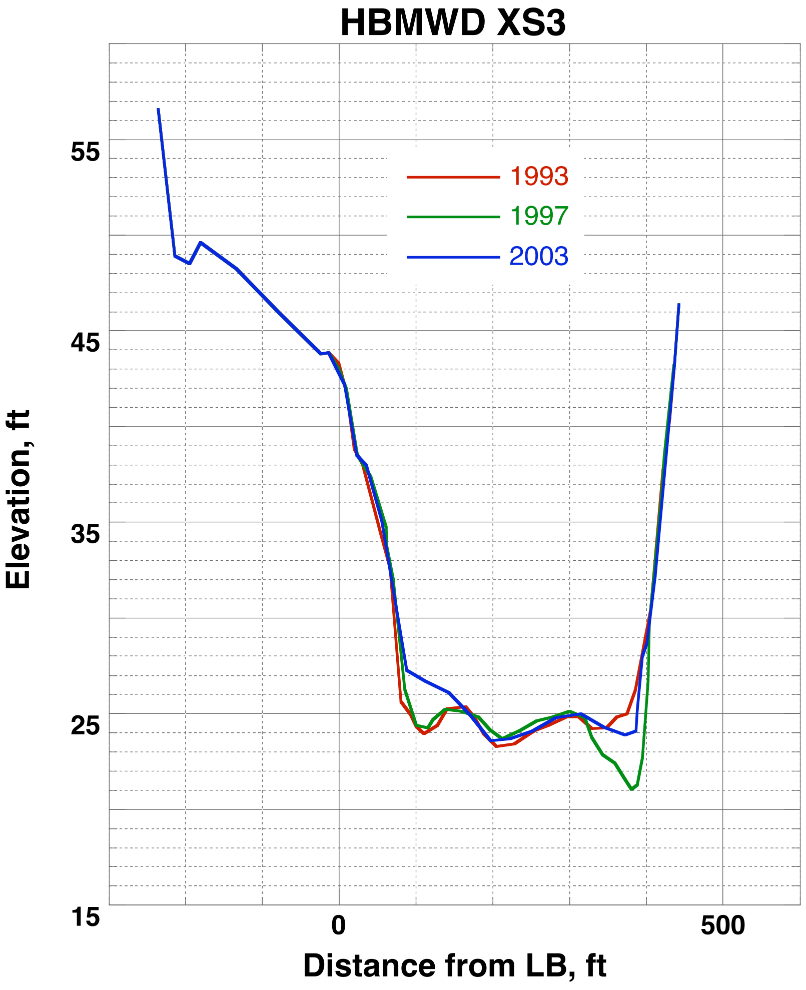
Essex Bar XS2

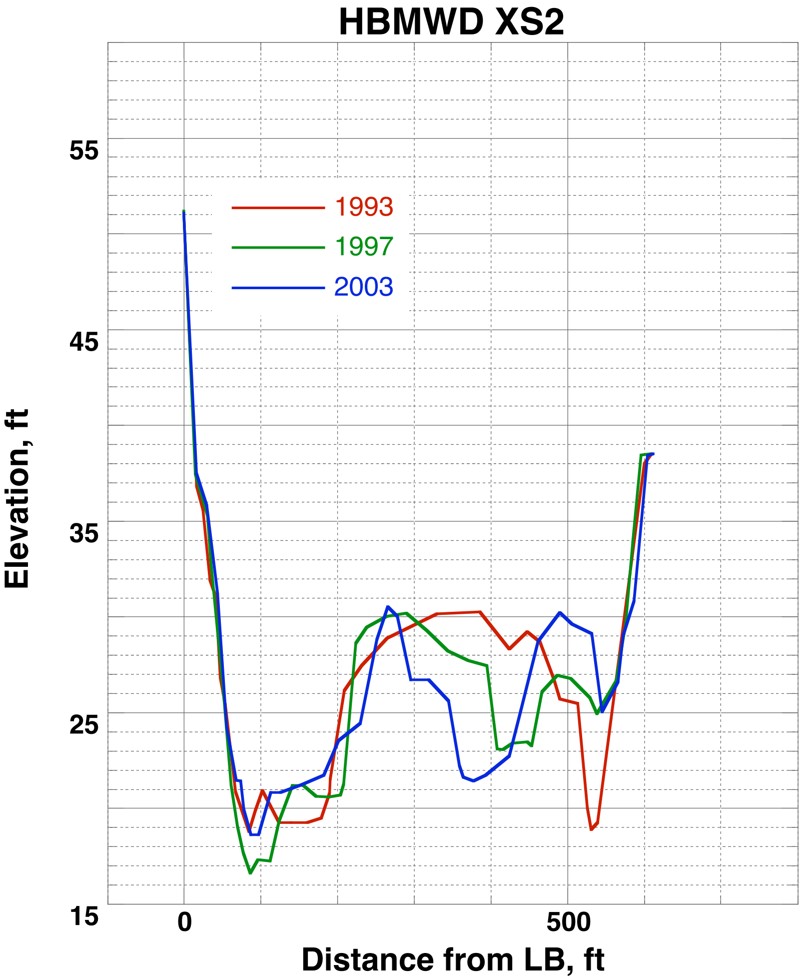
Essex Bar XS3

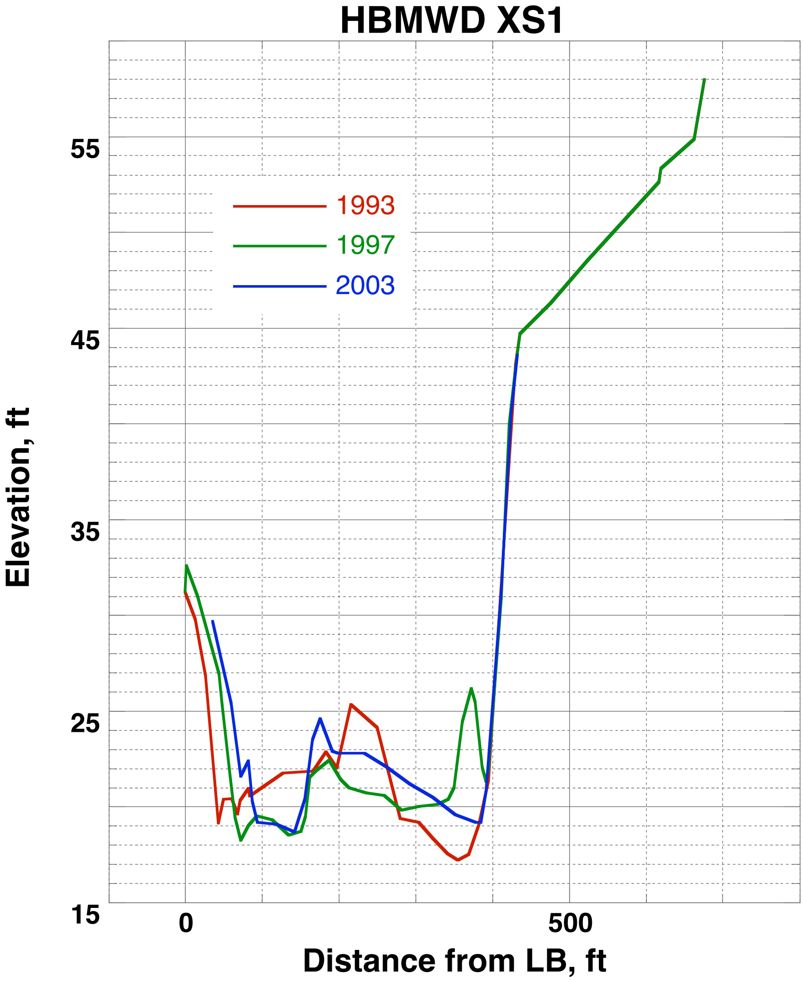


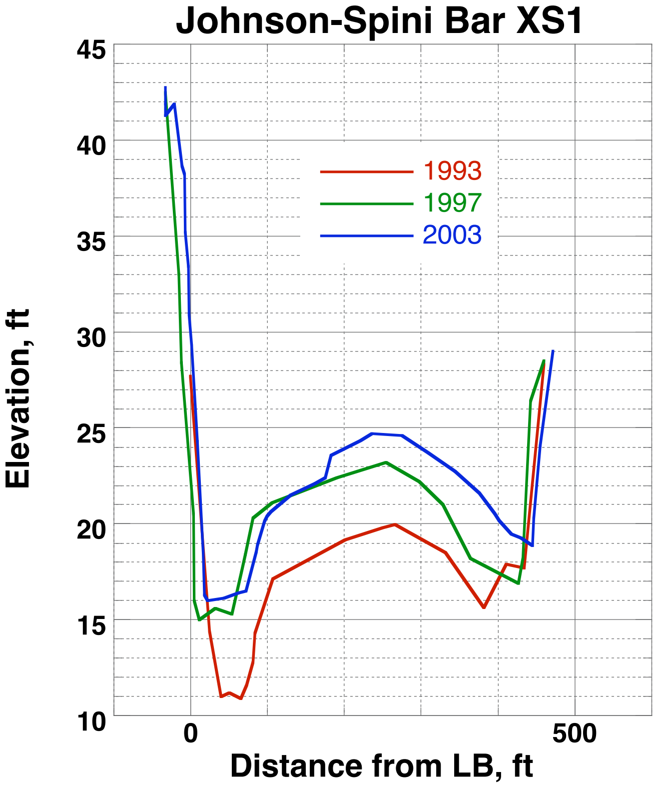

HBMWD XS5
Elevation, ft
Distance from LB, ft
70
60
50
40
30
20
0
500
1993
1997
2003

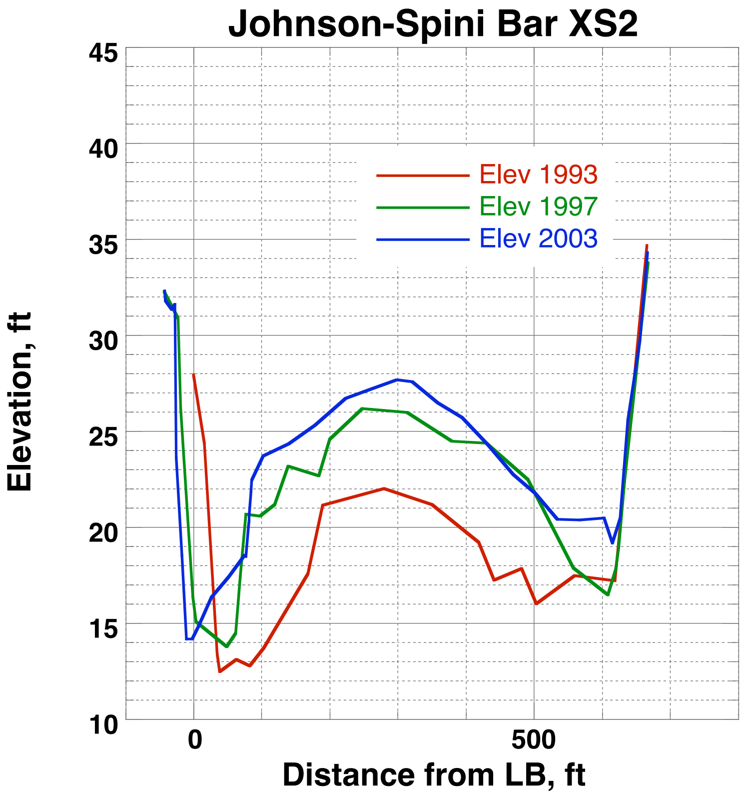

HBMWD XS4
1994
1997
2003
Elevation, ft
55
50
45
40
35
30
25
20
15
0
500
Distance from LB, ft

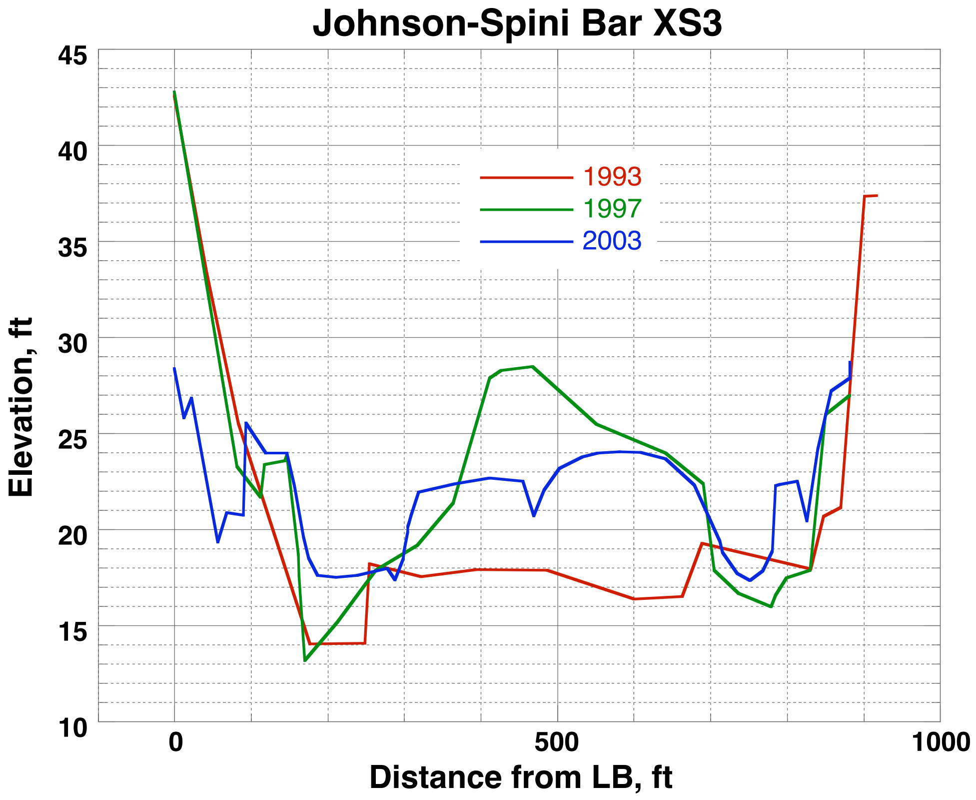

HBMWD XS3
1993
1997
2003
Elevation, ft
55
45
35
25
15
0
500
Distance from LB, ft

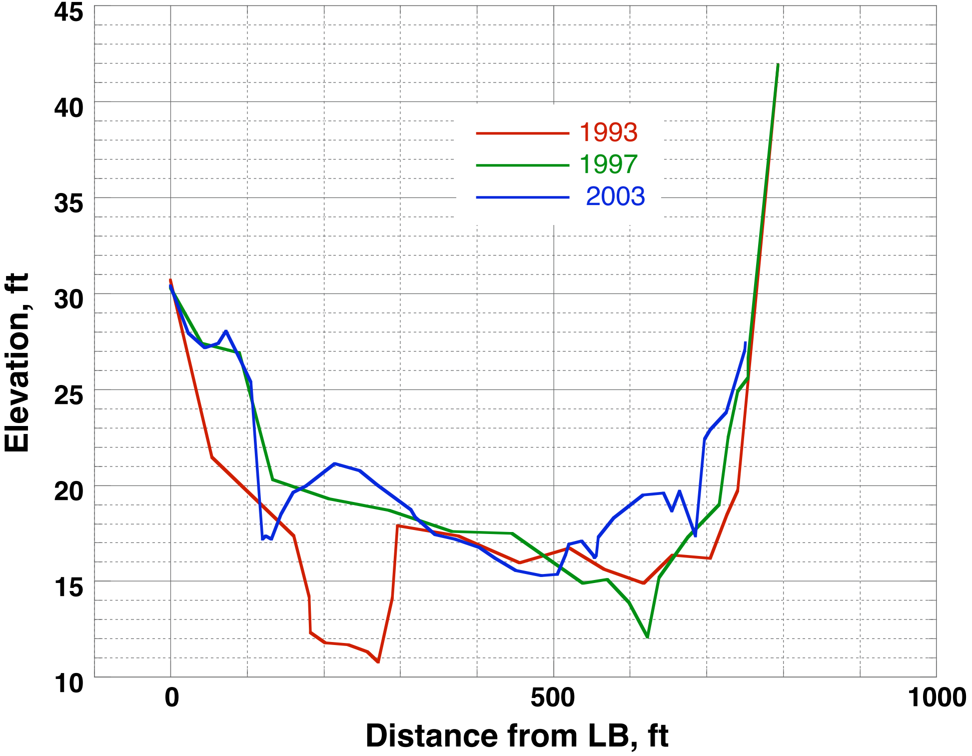

HBMWD XS2
Elevation, ft
55
45
35
25
15
0
500
Distance from LB, ft
1993
1997
2003

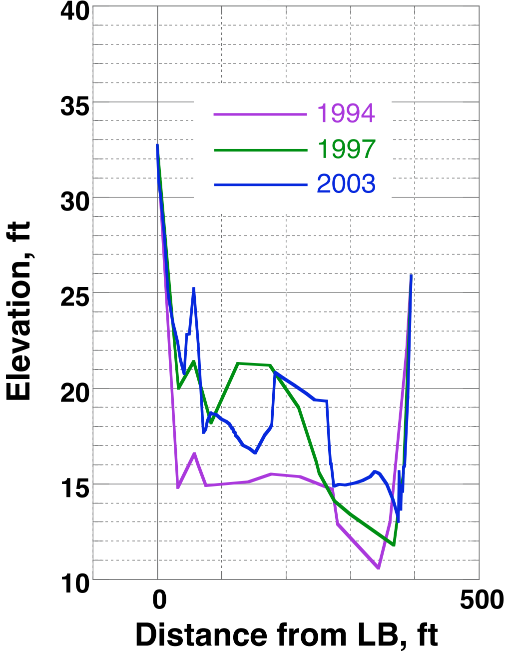

HBMWD XS1
55
45
35
25
15
0
500
Elevation, ft
Distance from LB, ft
1993
1997
2003

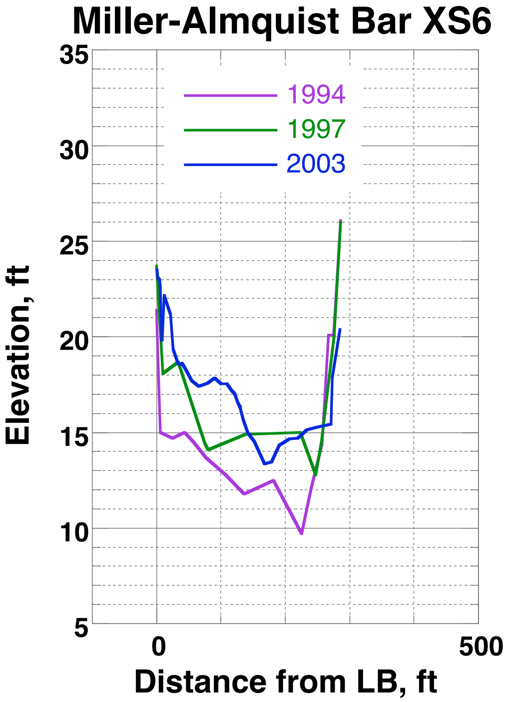

Johnson-Spini Bar XS1
45
40
35
30
25
20
15
10
0
500
Elevation, ft
Distance from LB, ft
1993
1997
2003

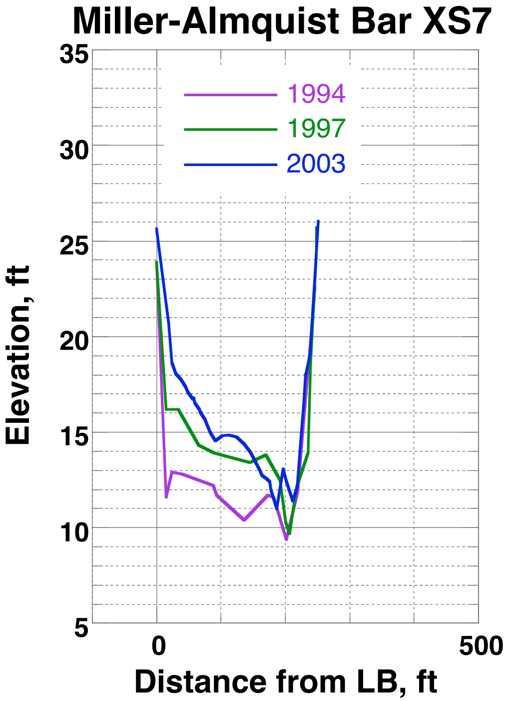

Johnson-Spini Bar XS2
Elevation, ft
Distance from LB, ft
45
40
35
30
25
20
15
10
0
500
Elev 1993
Elev 1997
Elev 2003

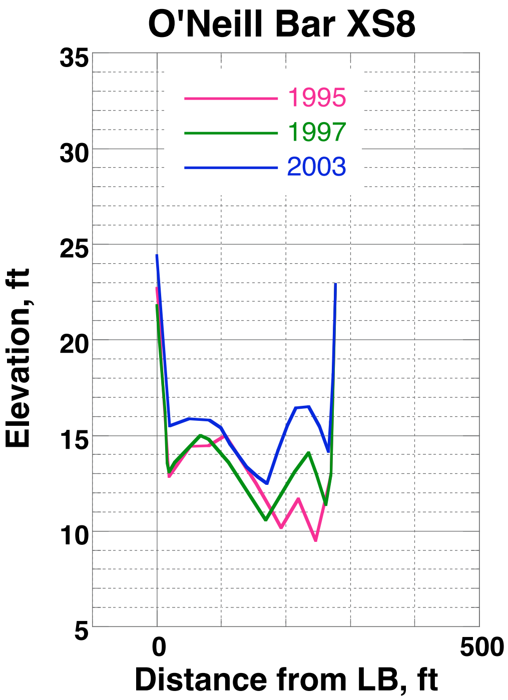

Johnson-Spini Bar XS3
Elevation, ft
Distance from LB, ft
45
40
35
30
25
20
15
10
0
500
1000
1993
1997
2003

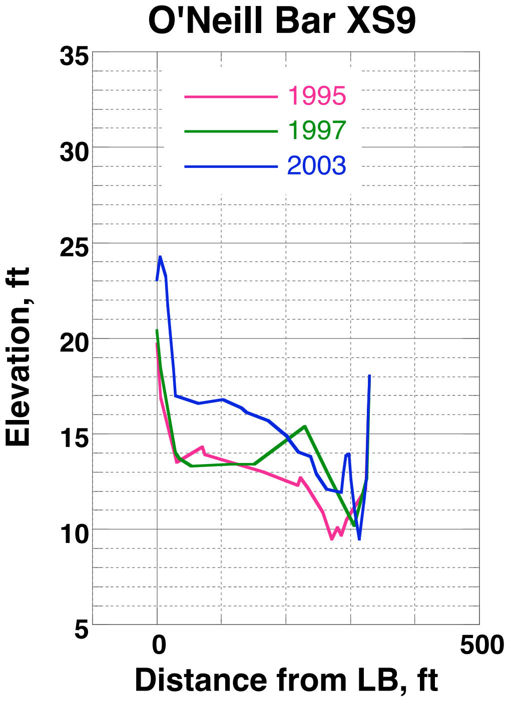

Johnson-Spini Bar XS4

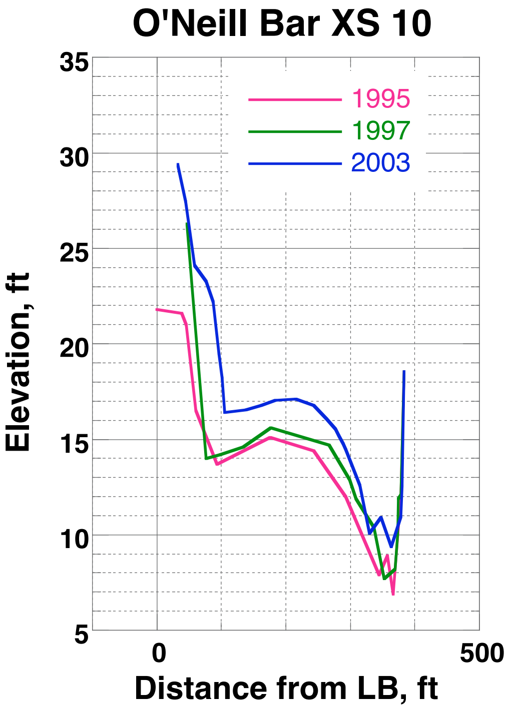

Miller-Almquist Bar XS5

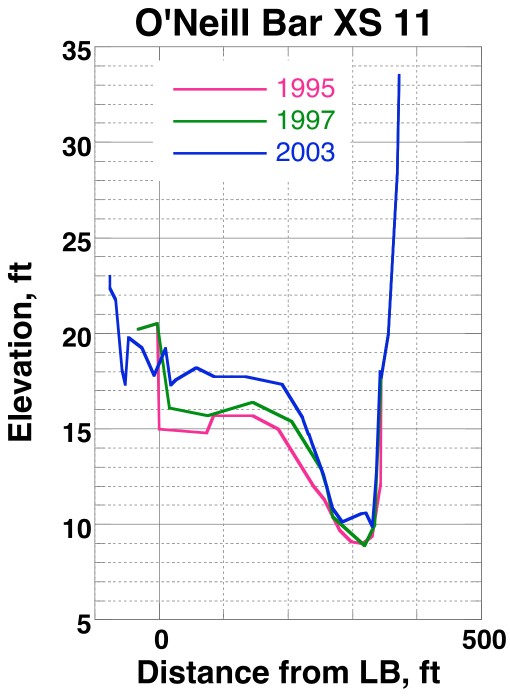

Miller-Almquist Bar XS6
1994
1997
2003
35
30
25
20
15
10
5
Elevation, ft
0
500
Distance from LB, ft

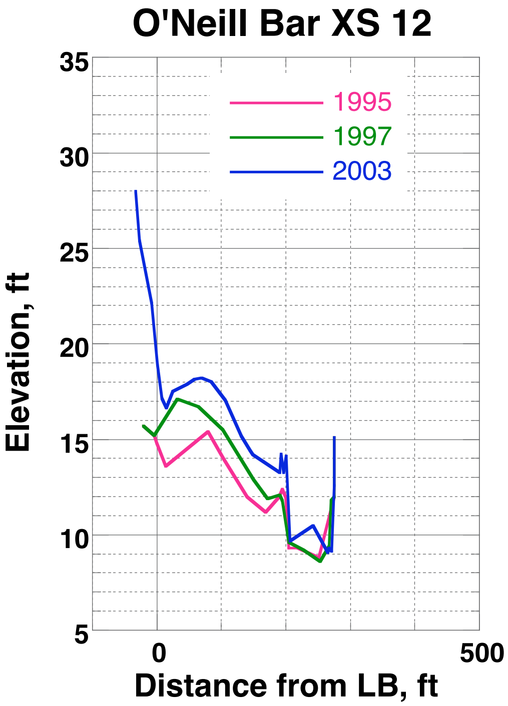

Miller-Almquist Bar XS7
1994
1997
2003
35
30
25
20
15
10
5
Elevation, ft
0
500
Distance from LB, ft


O'Neill Bar XS8


O'Neill Bar XS9


O'Neill Bar XS 10
1995
1997
2003
Elevation, ft
35
30
25
20
15
10
5
0
500
Distance from LB, ft


O'Neill Bar XS 11
1995
1997
2003
Elevation, ft
35
30
25
20
15
10
5
0
500
Distance from LB, ft


O'Neill Bar XS 12
1995
1997
2003
Elevation, ft
35
30
25
20
15
10
5
0
500
Distance from LB, ft