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Channel change and flooding, Skokomish River, Washington

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Abstract

Analysis of 45 years of cross-section data documents changes in channel width and bed elevation along the Skokomish River, Washington. The bed of the South Fork Skokomish incised over 1 m between 1940 and 1964, although both prior and subsequent to this period the mean bed elevation oscillated as much as 0.8 m with almost no cumulative change. In contrast, the mainstem Skokomish channel bed aggraded nearly 0.5 m between 1939 and 1944, oscillated at amplitudes up to 1 m with little net change from 1945 to 1964, and aggraded over 1.3 m between 1965 and 1997. In the late 1920s, prior to the onset of gaging station records, damming of the North Fork significantly reduced flow in the mainstem Skokomish. From the 1930s to the 1990s, peak discharge data for both the South Fork and the mainstem indicate no net increase in peak flows. Despite the reduced discharge from dam construction in the 1920s and no increase in peak flows during the following years, the frequency of overbank flooding in recent decades has increased on the floodplain of the mainstem. Systematic written descriptions and aerial photographs of the catchment from 1929 to 1992 document land use, including timber harvesting, road construction, and in-channel debris removal. The timing of changes in channel width and elevation imply that debris removal may have triggered periods of degradation and that near-channel and headwater land use potentially elevated the sediment supply to both reaches. Although direct land use causality is difficult to constrain, progressive reduction of channel conveyance in the mainstem as observed in USGS gage height trends does indicate that increased flooding on the mainstem Skokomish River resulted from aggradation, without an increase in peak discharges.

Keywords: Land use; Sediment transport; Channel geometry; Floods; Rivers; Olympic Peninsula

1. Introduction

The potential for land management to influence downstream flooding has been broadly acknowledged since early investigators discussed the effects of vegetation removal on erosion and runoff generation (Surell, 1841; Marsh, 1864). Although it is widely recognized that urbanization-related changes in basin hydrology can substantially alter flood frequency (e.g. James, 1965; Hollis, 1975; Booth, 1991; Moscrip and Montgomery, 1997), the effect of rural land management on downstream flooding remains more controversial. Increased flooding could arise from either hydrologic changes that increase peak flows or channel changes that reduce conveyance, and thereby trigger greater flooding without directly changing discharge quantity or timing. Most studies indicate that water yields increase after forest clearing (Bosch and Hewlett, 1982), but it is not clear as to whether industrial forestry significantly affects downstream flooding. The hydrologic response to timber harvest increases

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small, early season high flows, but researchers have not found consistently detectable effects on larger, flood-generating flows (Rothacher, 1970; Rothacher, 1973; Harris, 1973; Ziemer, 1981; Lyons and Beschta, 1983; Jones and Grant, 1996; Thomas and Megahan, 1998). In contrast to the past emphasis on changes in peak flows, little attention has been focused on the role of channel change in downstream flooding in forested mountain drainage basins. Here we use U.S. Geological Survey (USGS) gaging station records, supplemented with historical aerial photographs, to examine long-term channel change and its influence on floodplain inundation during a period of intensive upland management in the drainage basin of the Skokomish River, Washington. Analysis of frequent discharge sampling and cross-section surveys demonstrates that reduced channel conveyance has led to more frequent floodplain inundation despite reduced peak flows.

2. Study area

The Skokomish River drains 622 km^2 of forested terrain on the leeward side of the Olympic Peninsula, Washington (Fig. 1). The catchment discharges directly into Hood Canal, and much of the northern perimeter abuts Olympic National Park. Relief in the catchment is 424 m, and annual precipitation averages 3400 mm, most of which falls from November to February (Canning et al., 1988). The Skokomish catchment is underlain by thick deposits of glacial till and inter-glacial gravel, which is, in turn, underlain by basalt (Carson, 1970; Tabor, 1975). The lower portions of the basin consist of till deposited by the Vashon lobe of the Fraser Glaciation approximately 15,000 B.P. In the valley of the mainstem Skokomish, interglacial gravel interfingers with Holocene fluvial deposits of the Kitsap Formation. Eocene basalt outcrops in upper portions of the basin, in the gorge

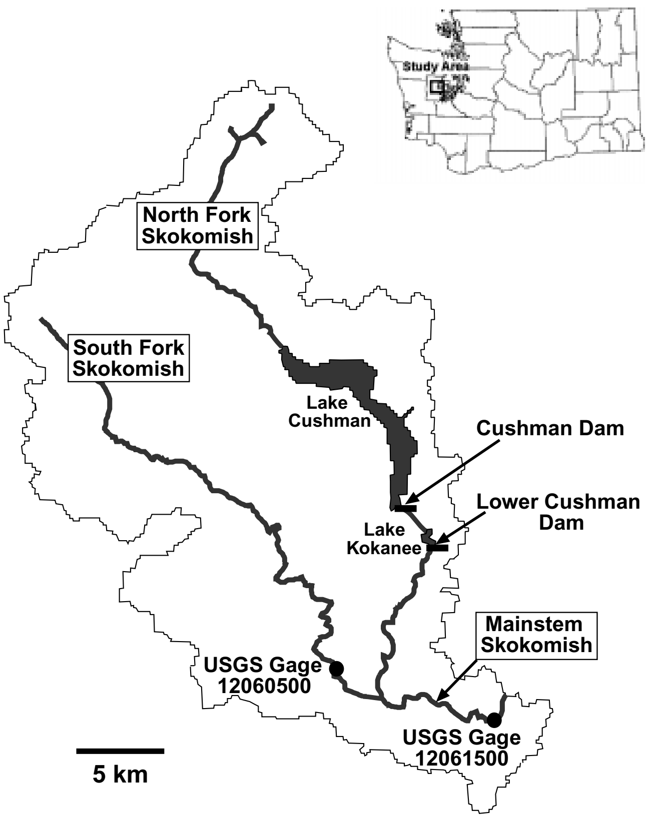

Fig. 1. General study area map outlining the Skokomish catchment and the locations of the South Fork and mainstem USGS gaging stations. The channel gradient decreases from 0.007 at the South Fork gaging station to less than 0.005 at the mainstem gaging station.

immediately above the lower South Fork gaging station, and in isolated locations along the mainstem.

The Skokomish catchment has an extensive history of land management. Beginning in the late 1800s, the Skokomish lowlands were transformed into dairy farms and agricultural land. Near-channel timber harvesting started in the late 1800s in the lowlands and progressed into the uplands by the 1940s. By 1992, 80% of the drainage basin of the South Fork had been harvested and thousands of miles of logging roads and railroad lines had been constructed in the catchment (KCM, 1993; Canning et al., 1988). Other practices, including gravel mining in the 1930s, channel straightening in 1953, and dike and berm construction circa 1971 also influenced the Skokomish River. In addition, construction of the Cushman and Lower Cushman dams in the late 1920s on the North Fork diverted approximately 40% of the mainstem flow directly to Hood Canal (Williams et al., 1985; Jay and Simestad, 1994). Despite overall flow reduction due to the dams, recurrent inundation of the floodplain of the mainstem Skokomish River has sparked controversy over the role of upland land management practices in flooding along the mainstem Skokomish.

3. Methods

We analyzed the entire available suite of USGS discharge data for the South Fork gaging station (#12060500) and the mainstem station (#12061500) (Fig. 1) in order to evaluate temporal changes in channel morphology. Original discharge measurement sheets (USGS Form 9-275-F) and supplementary discharge notes (USGS Form 9-275d) were used to develop cross-sections of the channel and to analyze other evidence of channel change recorded by USGS personnel. The South Fork and mainstem historically have been sites of geologic and aquatic habitat interest, and discharge measurements were taken on nearly a monthly basis throughout the period of record. The unusual frequency of measurements and long periods of record result in a substantial data set, with a total of 499 discharge surveys at the South Fork and 544 surveys at the mainstem. All discharge measurements post-date construction of the Cushman and Lower Cushman dams, and hence the mainstem flow record reflects the reduction in flow due to dam diversion.

The data record for the South Fork extends from 1932 to 1984 and the location of the gaging station was not altered during this period. Hence, all measurements are referenced to a consistent datum. At the mainstem gaging station, the available period of record covers 1932 to 1997. During this period, the gaging station was relocated three times. From 1956 to 1965, the gage location oscillated between the original gaging station and a location directly across the channel because fine sediment periodically restricted the intake valves. Measurements during this period were made at whichever gaging station exhibited clear intake valves. In July 1965, the gage was permanently relocated downstream at the Highway 101 bridge. Each new site was located within a kilometer from the original gaging point, and well-documented survey data and differences in elevation were used to correlate the data sets from each location of the mainstem gage.

3.1. Channel geometry determination

Each discharge estimate by USGS personnel was based on depth measurements at intervals across the channel and a gage height read from the station gage. From these data, we employed the following procedure to calculate mean bed heights, mean thalweg heights, and channel width. Both cable and wading measurements were collected at each site, with wading locations documented in terms of distance from the gaging station and a local control (i.e. stable large barform). As the control location may have changed with flow conditions, the distance above or below the gaging station, as noted on the measurement sheets, was used to select those measurements that could be considered consistent with the cable measurements. If the measurement location exceeded 200 ft (60.8 m) above or below the gage as documented on the measurement sheet, then the measurement was not used. For each discharge measurement, a channel depth cross-section was constructed by subtracting the gage height from total depth at each cross-sectional point. Data points from either bank were removed from each cross-section data set to restrict the analysis to variations in channel bed elevation. The data sets for each measurement were then used to calculate mean bed elevation and channel width. These parameters and gage height/discharge relationships were evaluated for changes over time. Distinct phases of channel behavior were identified through changes in both long-term trends in mean bed elevation and the amplitude of finer-scale oscillations.

3.2. Statistical analysis of width changes

Paired *t*-tests were used to evaluate the significance of width changes for the South Fork and mainstem, following Beschta (1983) and testing for significance at the $\alpha = 0.05$ confidence level. To isolate times of distinct channel change, periods of statistically significant width change were subdivided and paired *t*-tests were reconducted. Following Hoey (1994), we also implemented an analytical approach to identify periods of aggradation and degradation for the two channels. This approach uses distance between channels and width changes over time to calculate aggradation and degradation magnitudes. Volumetric changes (ΔV), and hence aggradation and degradation trends, between the South Fork and mainstem reaches were determined through using the following equation and assuming that $\Delta\bar{z}$and w_i vary linearly between the reaches:

$$\Delta V = w_i \Delta\bar{z}_i L(2 + a + b + 2ab)/6 \tag{1}$$

where w_i is the bank-to-bank width (m) at reach i; $\Delta\bar{z}_i$ is $\Delta A/w$ (m); A is cross-sectional area (m^2); L is the distance between reaches i and j (m); a is w_i/w_j; and b is $\Delta\bar{z}_i/\Delta\bar{z}_j$.

Volumetric changes were converted to elevation changes for presentation clarity following:

$$\Delta\bar{h}_i = \frac{\Delta V}{w_i L B} \tag{2}$$

where $\Delta\bar{h}_i$ is average elevation change (m) at reach i, and B is $(2 + a + b + 2ab)/6$.

Changes were computed over ten-year intervals to assess long-term trends in aggradation and degradation. Cross-sectional area and width data were extracted from each discharge sheet and averaged for each period of interest. Distance data were updated for the time periods in which the mainstem gaging station was relocated, with distance between the reaches measuring 8280 m from 1932 to 1965 and 9240 m from 1965 to the end of the record. Absolute aggradation and degradation values also were determined through time trends in the mean bed heights for each reach over parallel periods of interest.

3.3. Characterization of land management

The continuous record of discharge measurements and supplementary discharge notes record changes in land use of the Skokomish catchment. Impressively systematic written descriptions in the remarks section of the discharge measurements (i.e. 88% of South Fork forms and 73% of mainstem forms contained written documentation), and additional notation on supplementary discharge notes document near-channel timber harvest, bedform changes, and in-channel debris removal near the gage locations. The nearly monthly documentation associated with the discharge measurements constrained the timing of many of the land use activities in the vicinity of the gaging stations. To supplement the written description of changes in land use, we evaluated harvested areas, land use changes, and road construction apparent on available sets of aerial photographs of the catchment (1929, 1944, 1952, 1965, 1981, and 1992). The timing of land use activities determined through both written descriptions and aerial photo evaluation aided interpretation of trends in the mean bed elevation.

4. South Fork channel change

Changes in bed elevation define three distinct phases of channel response for the South Fork (Fig. 2). The first phase (1932–1944) is defined by initial slight aggradation and moderate-amplitude fluctuations in mean bed elevation from 1932 to 1940, followed by minor incision from 1940 to 1944. The second phase of response (1944–1964) began with low-magnitude aggradation (1944–1950) followed by subsequent degradation from 1951 to 1964. The final phase of bed response (1964–1984) suggests stabilization of mean bed height. Land management activity during these three phases provides insight into the potential causes for each stage of channel response.

4.1. 1932–1944

From 1932 to 1940 the channel was characterized by a fairly stable mean bed elevation, but from 1940 to 1944 the channel incised (Fig. 2). From 1932 to 1935,

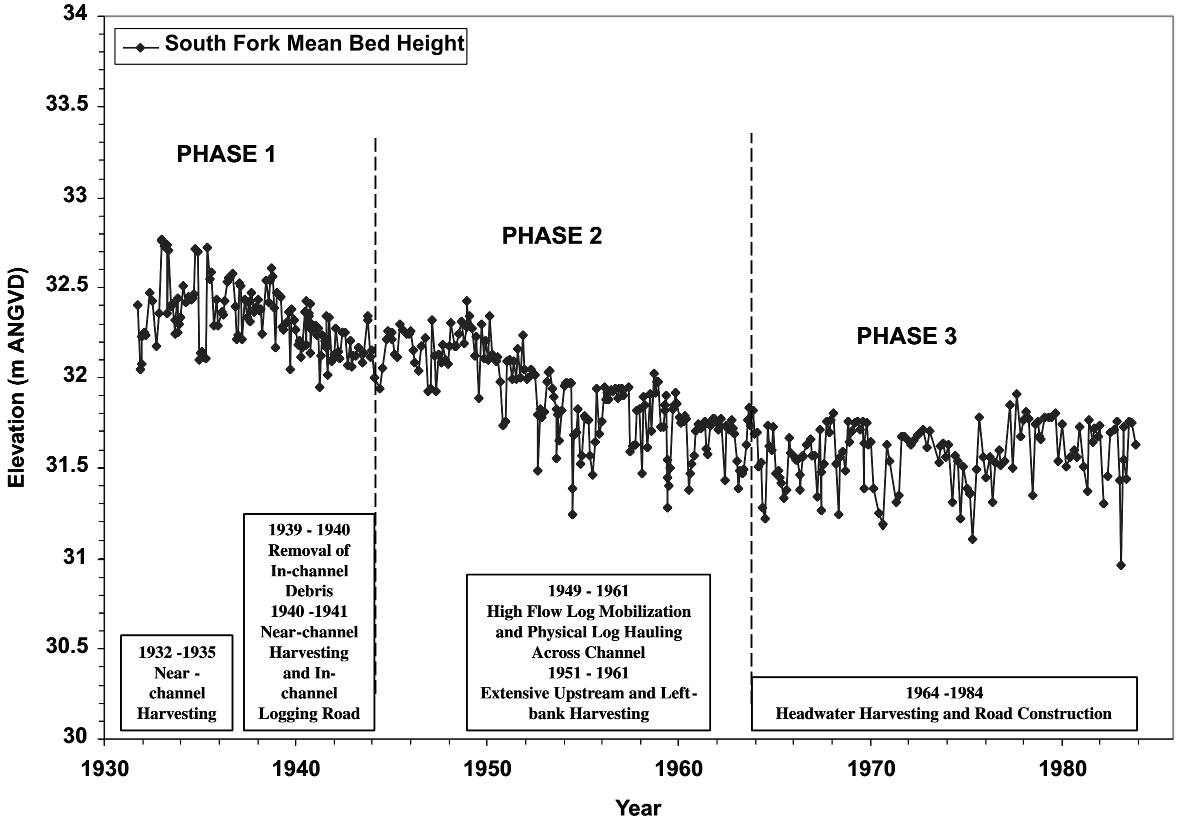

Fig. 2. Temporal changes in mean bed elevation, phases of channel response, and general land management activities for the South Fork Skokomish River. ANGVD is above national geodetic vertical datum.

the mean bed height aggraded slightly and fluctuated with approximately 0.6 m oscillations. Throughout this time period USGS personnel documented an influx of "loose gravel" into the channel and noted that "drift [wood debris] comes down often" (USGS Discharge Sheets, various dates, 1932 to 1934). High flows between 1933 and 1935 may have initiated incision, but the bed elevation quickly recovered to a pre-flood elevation (Fig. 3). Land use activities from 1932 to 1935, as noted on USGS discharge sheets, consisted primarily of near-bank timber harvesting along the South Fork, near and upstream of the gaging station. Between 1935 and 1939, the channel exhibited seasonal fill and scour, and the amplitude of the bed oscillations decreased to about 0.3 m. By early 1939, USGS personnel had begun to note "piles of logs" on the section control (USGS Discharge Sheet, January 12, 1939), and in late 1939, there was documentation of a "river full of logs and debris" (USGS Discharge Sheet, November 24, 1939), suggesting an increased amount of woody debris in the channel. A December 1939 high flow event and in-channel debris removal in early 1940 correspond to a time of net bed lowering (Figs. 2 and 3).

The near-channel disturbances continued into 1940, and channel response consisted of minor aggradation followed by degradation beginning in mid-1941. USGS personnel noted fine-grained sediment input early in 1940 and "loose gravel" later that same year; discharge sheets document and aerial photos support the presence of landslides "in vicinity of gage" (USGS Discharge Sheet, March 3, 1941) and in-channel logjams from 1940 to mid-1941. Proximal disturbances consisted of near-channel timber harvesting "immediately above gage" (USGS Discharge Sheets, September 5, 1940 and October

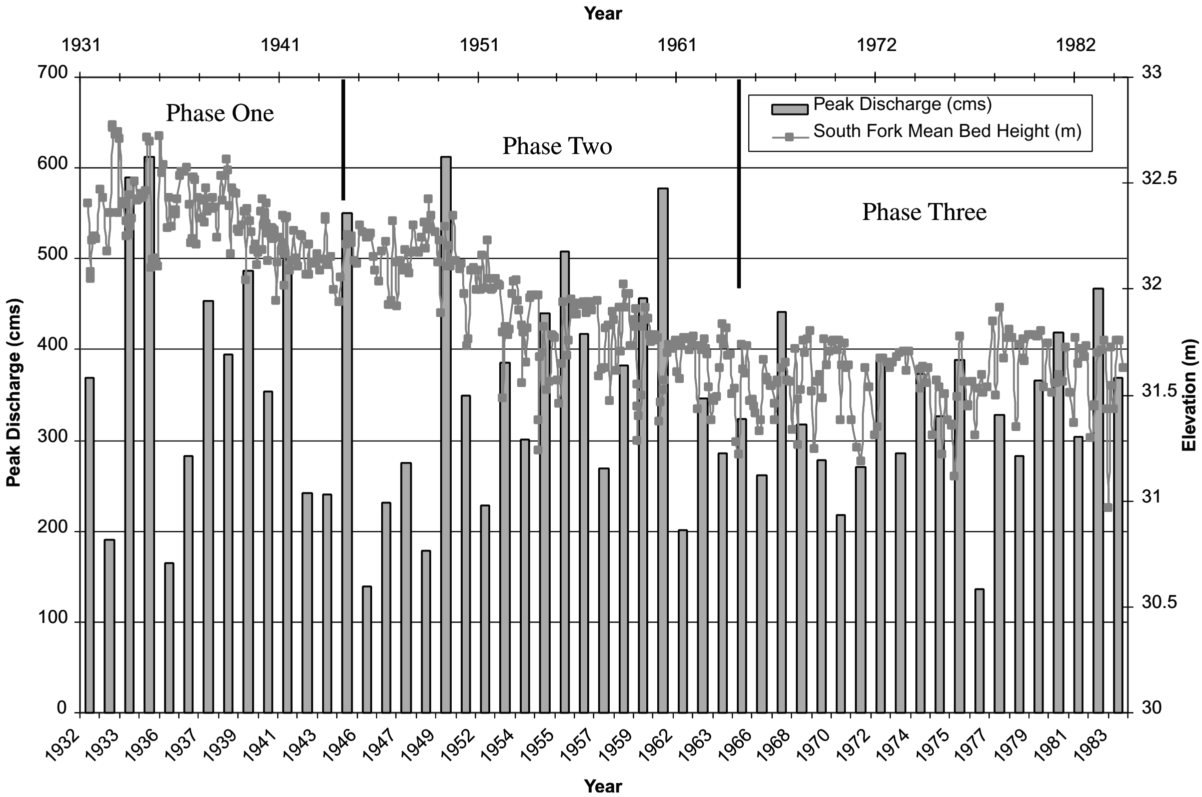

Fig. 3. Temporal changes in mean bed elevation superimposed on peak discharge values for the South Fork Skokomish River.

16, 1940), and the late 1941 development of an in-channel logging road. The trend in mean bed height indicates channel degradation from late 1941 to 1944, with the mean bed elevation decreasing by about 0.3 m. This degradation corresponds to the frequent documentation of "running drift" on USGS discharge sheets. Throughout the initial aggradation and latter degradation during this response phase, the change in channel width was statistically insignificant (Fig. 4a).

4.2. 1944–1964

Channel response from 1944 to 1964 was characterized by gradual channel incision (Fig. 2). A trend of lowered bed elevation began in a high flow event during 1949 (Fig. 3), which USGS personnel documented as introducing fine sediment and wood debris to the reach. This trend continued until 1964, with a marked increase in bed height oscillations from 1951 to 1961. Such change in the system corresponds to a period of upstream and extensive local left bank timber harvesting, in the immediate vicinity of the gage. Both written USGS documentation (USGS Discharge Sheets, various dates 1951 to 1961) and aerial photographs indicated increased timber harvesting from 1944 to 1965. USGS personnel further noted a high-water event that mobilized logs in the channel in 1954 and loggers dragging logs across the channel in 1956. Throughout the period of degradation from 1950 to 1964, the mean bed height decreased over 1 m, and the channel width increased more than 20% (Figs. 2 and 4a).

4.3. 1964–1984

From 1964 to 1984, the channel exhibited no distinct aggradation or degradation (Fig. 2), despite three distinct peak flow events in excess of 400 cms (Fig. 3). Bed height oscillations of 0.3–0.8 m continued, although no significant change in width

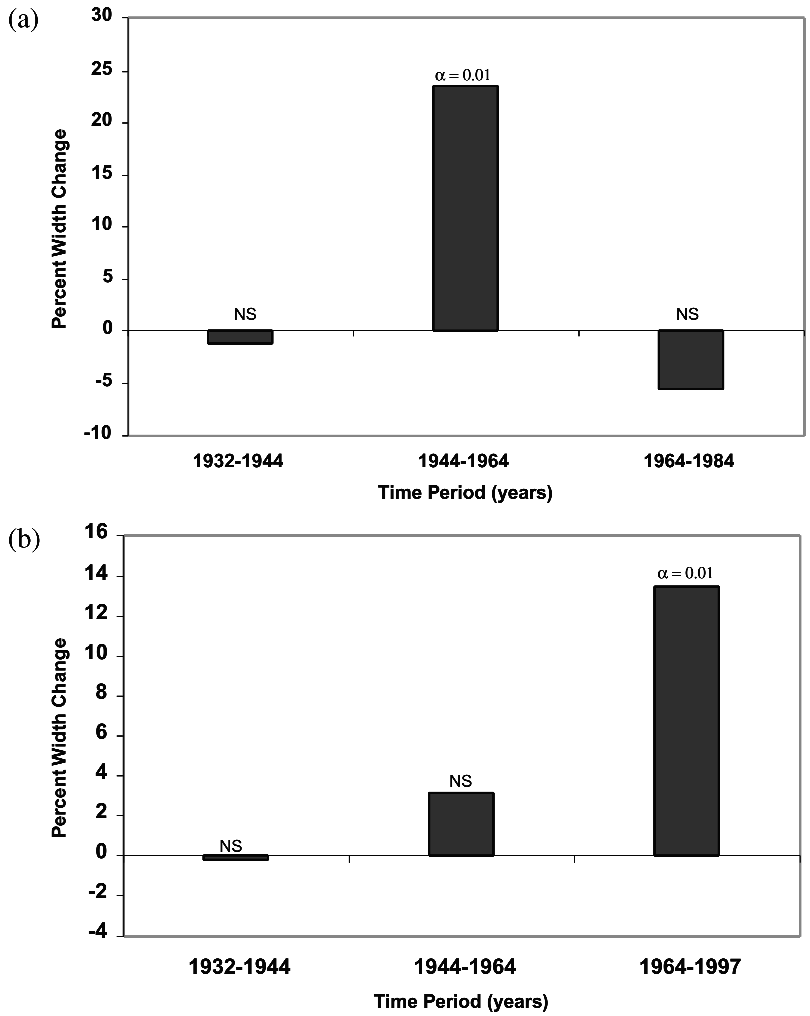

Fig. 4. Significance of percent width change for the: (a) South Fork; and (b) mainstem Skokomish. NS denotes no significant change; α denotes level of significance. (a) Width change was significant to $\alpha = 0.01$ for 1944–1964, and insignificant for 1932–1944 and 1964–1984. (b) Width change was significant to $\alpha = 0.01$ for 1964–1997, and insignificant for 1932–1944 and 1944–1964.

was noted for this period (Fig. 4a). Throughout this time, no near-bank logging was documented on the USGS discharge sheets, and the main land use activity, as observed in 1965 and 1981 aerial photos and recorded in USGS discharge sheets, consisted of upland road construction and timber harvesting.

5. Mainstem channel change

Changes in channel geometry for the mainstem Skokomish are well described by the same three time periods that define phases of channel response on the South Fork (Figs. 5 and 6). The first phase (1932–1944) exhibited both an initial incision from 1932 to 1938, and subsequent aggradation from 1939 to 1944. The second phase (1944–1964) was characterized by bed elevation fluctuations of 0.3–1 m in amplitude. The final phase of response (1964–1997) involves accelerated aggradation, and a dampening of the oscillations in mean bed height. Evidence of land management activity during these three phases of response provides insight into the potential causes of changes in channel width and bed elevation.

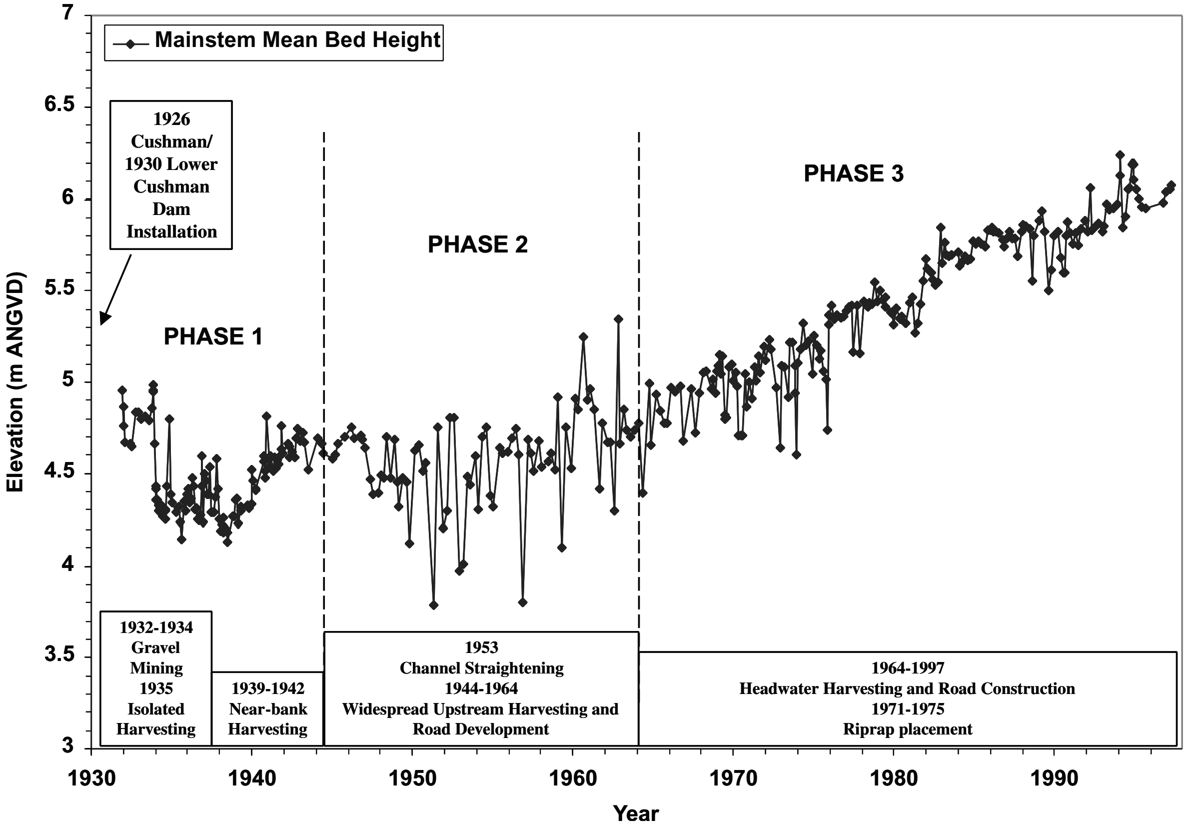

Fig. 5. Temporal changes in mean bed elevation, phases of channel response, and general land management activities for the mainstem Skokomish River. ANGVD is above national geodetic vertical datum.

5.1. 1932–1944

Initial response on the mainstem involved incision of nearly 0.5 m from 1932 to 1944 (Fig. 5). This rapid incision spans a period of intense channel-proximal disturbances: 1932–1934 gravel mining at the gage, and along the left bank abutting the gage, for construction of Highway 101; and the 1934 construction of the highway (which introduced gravel and forced the upstream relocation of USGS channel control (USGS Discharge Sheet, June 5, 1934)). From 1939 to 1944 the channel aggraded to nearly its original 1932 elevation. Predominant land use during the 1939 to 1944 period consisted of localized near-bank timber harvesting. During this period, the change in channel width was insignificant (Fig. 4b).

5.2. 1944–1964

The period from 1944 to 1964 was characterized by an enhanced amplitude of bed surface fluctuations, although the mean bed elevation throughout Phase Two did not change appreciably (Fig. 5). This phase of channel response coincides with the onset of widespread upstream timber harvesting and road development within the catchment. In 1947, the channel also began to exhibit bed elevation oscillations of up to 1 m and USGS notes state that the channel bed began to fine. The extreme bed elevation fluctuations continued until 1964. In 1953, channel straightening eliminated the bend upstream of the gage. Width change during this period was insignificant (Fig. 4b).

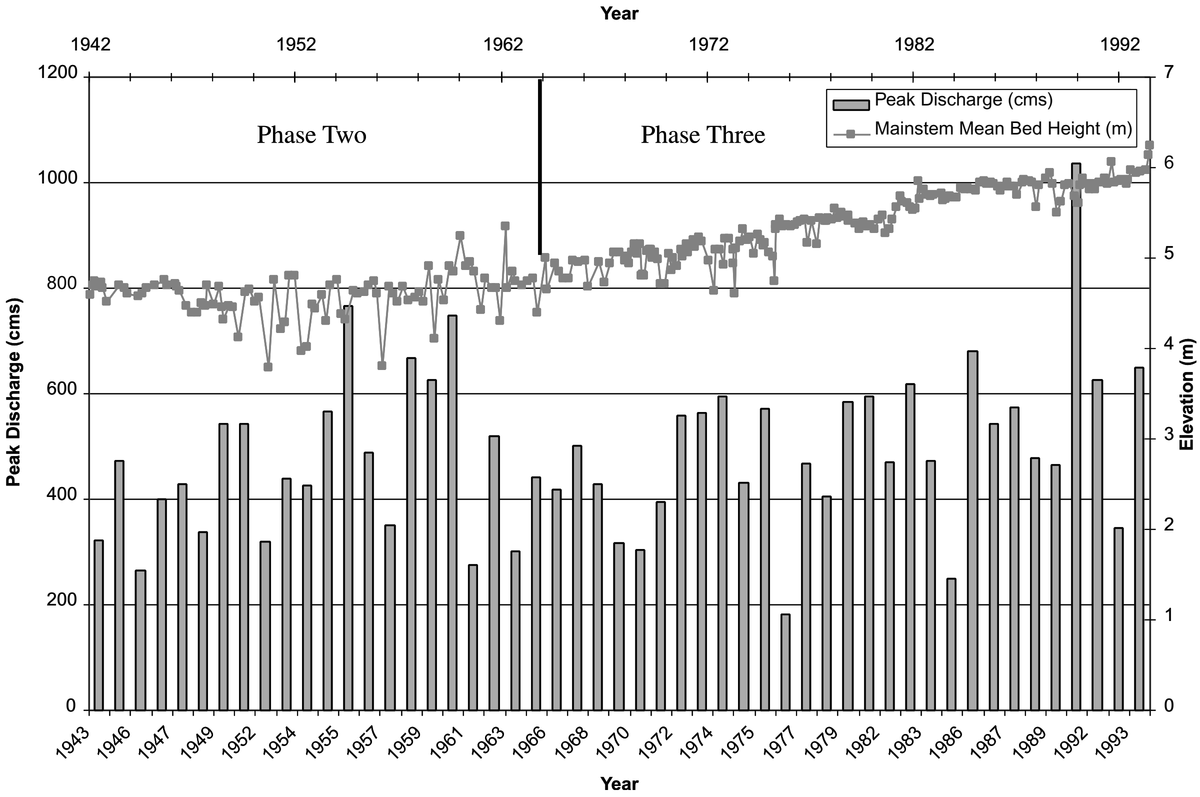

Fig. 6. Temporal changes in mean bed elevation superimposed on peak discharge values for the mainstem Skokomish River. Due to a lack of continuous peak discharge data from 1932 to 1943, the time period presented here covers 1943–1993.

5.3. 1964–1997

From 1964 to 1997 the mainstem aggraded and USGS discharge forms document significant channel filling and the formation of a soft channel substrate from fining with "mud". Total elevation gain was over 1.3 m and the channel width increased by over 12% (Figs. 4b and 5). This aggradation eventually forced relocation of the gaging station, as the intake valves were beginning to become isolated from the main channel. Between 1971 and 1975, riprap and natural berm material were emplaced along the right bank of the channel, upstream of the gaging location (USGS discharge sheets, various). Perhaps coincidentally, the distinct bed-height oscillations ceased after 1976. Land use practices during this phase consisted of upland timber harvesting and road construction, primarily upstream of the South Fork gaging station.

6. Peak flows, stage–discharge relation and floodplain inundation

Evaluation of peak discharge recurrence intervals and stage height for each phase of channel response in both the South Fork and mainstem indicates that the recent flooding along the mainstem is a result of an altered stage–discharge relation. Analysis of peak discharge recurrence intervals for each phase of channel response reveals that the peak discharge is either decreasing over time, or remaining relatively unchanged for both reaches (Fig. 7). Although neither the South Fork nor the mainstem exhibit an increase in peak discharge recurrence intervals throughout the period of record, both reaches display systematic changes in the stage, or water surface elevation as reflected in gage height measurements, at any given discharge. For the South Fork, the flow stage–discharge relation indicates a lowering of the water

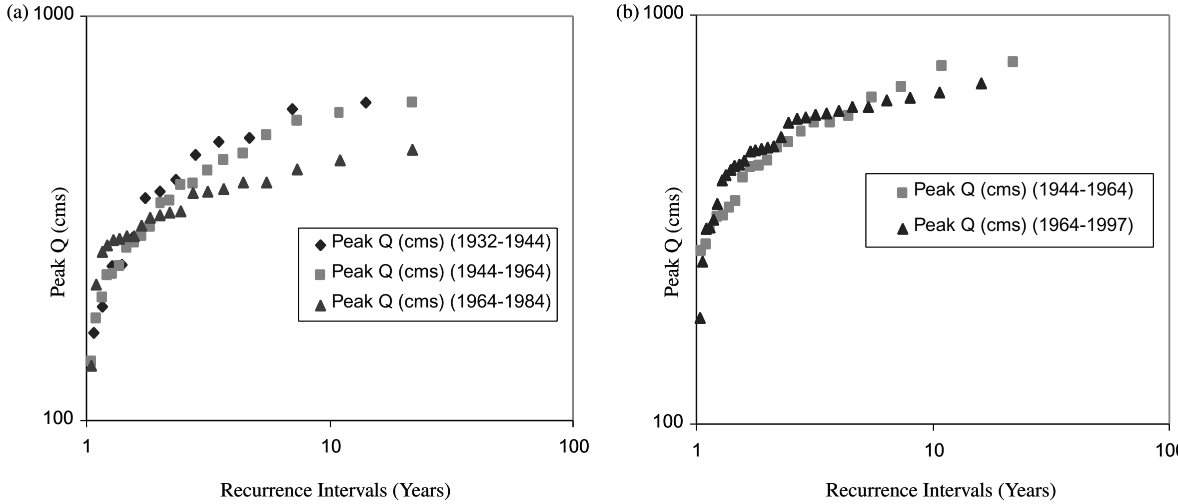

Fig. 7. Recurrence Interval vs. Peak Discharge for the: (a) South Fork; and (b) mainstem Skokomish. (a) The trends in recurrence interval over time indicate a generally decreasing discharge regime for low and high recurrence intervals. (b) The trends in recurrence interval over time indicate a relatively unchanged discharge regime for low recurrence intervals and a decrease in the discharge regime for high recurrence intervals.

surface elevation for a given discharge until the stage–discharge relationship stabilized in 1964 (Fig. 8). This trend parallels the entrenchment of the South Fork channel bed and the beginning of apparent bed elevation stability in 1964. In contrast, the mainstem flow stage versus discharge relationship exhibits an increased stage for any given discharge, coinciding with an aggrading channel bed (Fig. 9). Such reduction in the requisite discharge for a given stage, together with a relatively unchanged peak discharge regime, indicates that recent mainstem flooding is due to aggradation within the channel. Without simultaneous aggradation of the floodplain, the higher stage associated with smaller discharges allows for a higher frequency of floodplain inundation on the mainstem.

7. Discussion

The South Fork and mainstem reaches of the Skokomish River exhibited different styles of response during the period of record. The South Fork channel initially incised, and then stabilized its mean bed elevation after 1964, although significant bed-elevation fluctuations continued. In contrast, the mainstem experienced a short period of degradation in the early 1930s, after which the channel recovered its initial elevation and began to exhibit significant bed oscillations. After 1964, these oscillations gave way to gradual aggradation, which totaled over 1.3 m by 1997.

The parallel timing of South Fork debris removal and in-channel perturbations with degradation of the bed suggests that the in-channel events caused the observed South Fork channel response. In contrast, the presence of the Cushman and Lower Cushman dams, which were built prior to installation of the gaging stations, raises the possibility that aggradation along the mainstem resulted from dam construction. Such causality hinges on the idea that reduced flow to the mainstem lowered the transport capacity of the mainstem reach. However, it is difficult to ascribe the aggradation of the mainstem solely to reduced discharge from the dammed North Fork, because damming should have caused mainstem aggradation relatively quickly. This is especially true given the comparatively low overall discharge regime from 1932 to 1944, the first recorded period of post-dam discharge. It is also difficult to attribute observed channel changes to altered peak flow frequency, as the discharge data show no discernible increase in peak flows for either reach. We infer that alterations in sediment load from proximal and distal harvesting-related activities and road construction, followed by

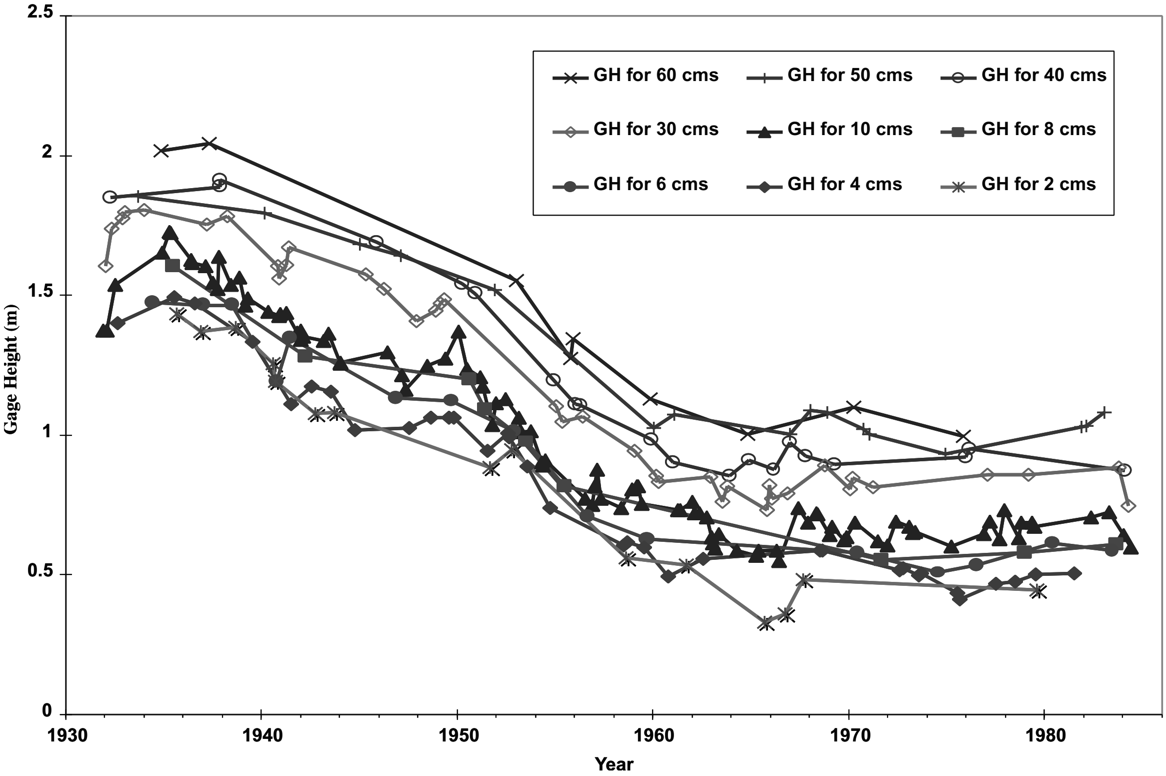

Fig. 8. South Fork discharge/gage height relationship. Profile parallels the temporal changes in mean bed height, with an apparent stabilization of the discharge/gage height trend with time. GH represents gage height corresponding to a given discharge (cms).

debris removal from land management, triggered the observed South Fork channel response. Likewise, we infer that an increased sediment load from proximal harvesting, upstream harvest-related activities, and South Fork incision, combined with a reduced transport capacity from dam construction, were responsible for the observed mainstem channel response.

7.1. South Fork

The South Fork generally incised from 1932 to the mid-1950s, and subsequently exhibited distinct oscillations in bed elevation until the 1960s. The presence of wood debris in stream channels may modify hydraulic properties and bedforms, and removal of debris can result in dramatic and rapid reduction in bed elevation and hydraulic roughness (Macdonald and Keller, 1987; Shields and Smith, 1992; Smith et al., 1993a,b). We suspect that harvesting of riparian forests in conjunction with the removal of wood debris from the South Fork, together with a late 1939 high flow event, initiated channel incision from late 1939 to 1940. In the second, more extensive period of degradation (late-1940–1944), the drop in channel elevation coincided with debris removal at the gage location to clear the channel for development of a temporary in-channel logging road. During this same period, “loose gravel” and “running drift” were transported through the system.

Channel response was limited to bed oscillations about a fairly constant mean bed height from 1961 to 1984 when active timber harvesting had progressed further into the upland areas of the catchment. We interpret the bed elevation fluctuations as pulses of sediment in transport through the system. These bed elevation oscillations increased in amplitude in the 1950s, a time in which the South Fork channel width was increasing and harvesting was becoming extensive in the headwaters. However, the bed did degrade during this time of high-amplitude bed

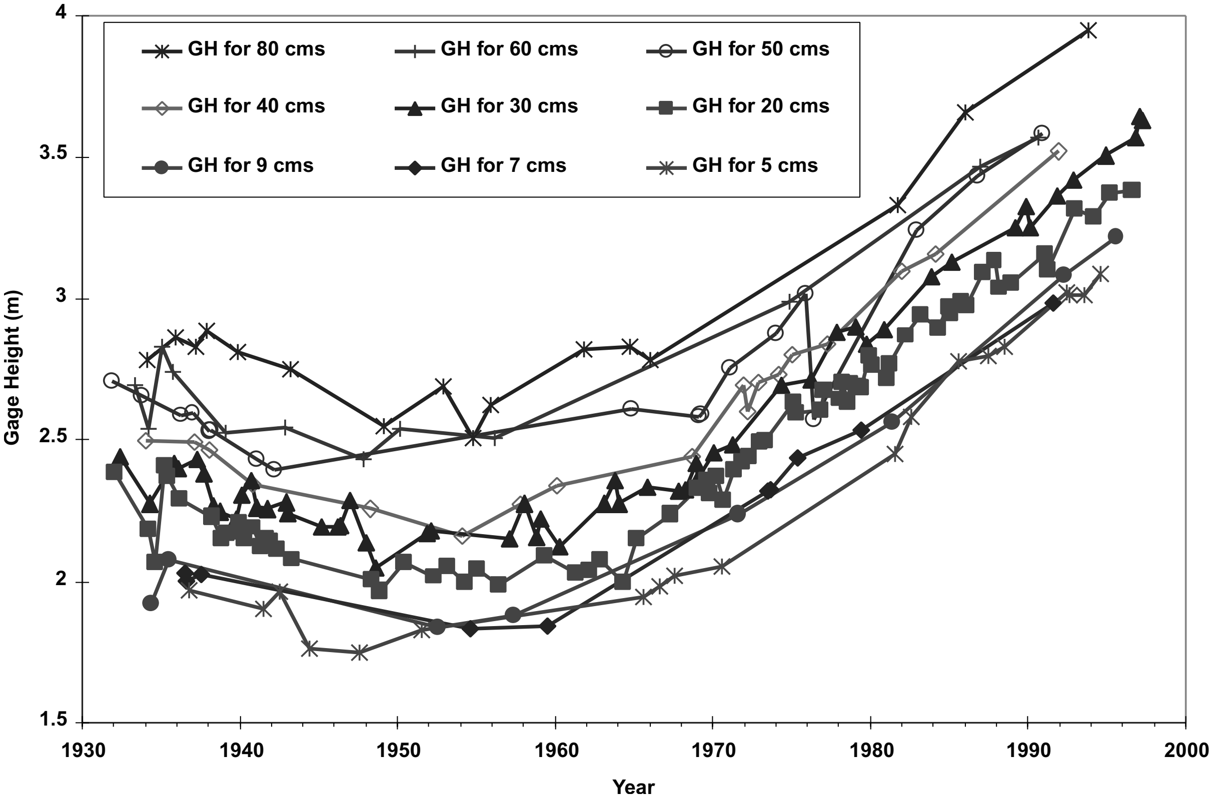

Fig. 9. Mainstem discharge/gage height relationship. Profile parallels the temporal changes in mean bed height, with a marked increase in the gage height for any given discharge regime over time. GH represents gage height corresponding to a given discharge (cms).

oscillations from 1949 to nearly 1961, likely due to debris removal, in-channel perturbations and subsequent sediment mobilization. We interpret these responses as recording a substantial transfer of sediment to the mainstem Skokomish River.

7.2. Mainstem

As with the South Fork, the timing of land management activities and channel changes suggests that a variety of influences played a role in initiating the trends observed in the mainstem bed elevation. From 1932 to 1934, the mainstem exhibited substantial and rapid degradation. During this time, Highway 101 was constructed less than 1 km downstream of the gage, and heavy equipment was employed to extract gravel from the mainstem. After gravel mining ceased, the channel recovered some of the elevation loss, but it was not until the first noted logging in the area in 1939 that the channel began to aggrade rapidly. Aggradation continued until 1944, when harvesting progressed upstream toward the headwaters. From 1944 to 1964, the channel exhibited enhanced bed height oscillations that we interpret as pulses of sediment in transit through the system. Because the appearance of these bed height oscillations corresponds to the time when channel width was increasing for the South Fork, and upland harvesting and road development became particularly extensive, we infer that they reflect sediment input from channel proximal disturbance and accelerated upstream sediment influx. The hypothesis of an elevated sediment supply to the mainstem is supported anecdotally by the notes of USGS personnel from this time, such as "this channel is a mess: there are bars and riffles everywhere!" (USGS Discharge Sheet, September 4, 1957).

Comparison of the timing of net incision of the

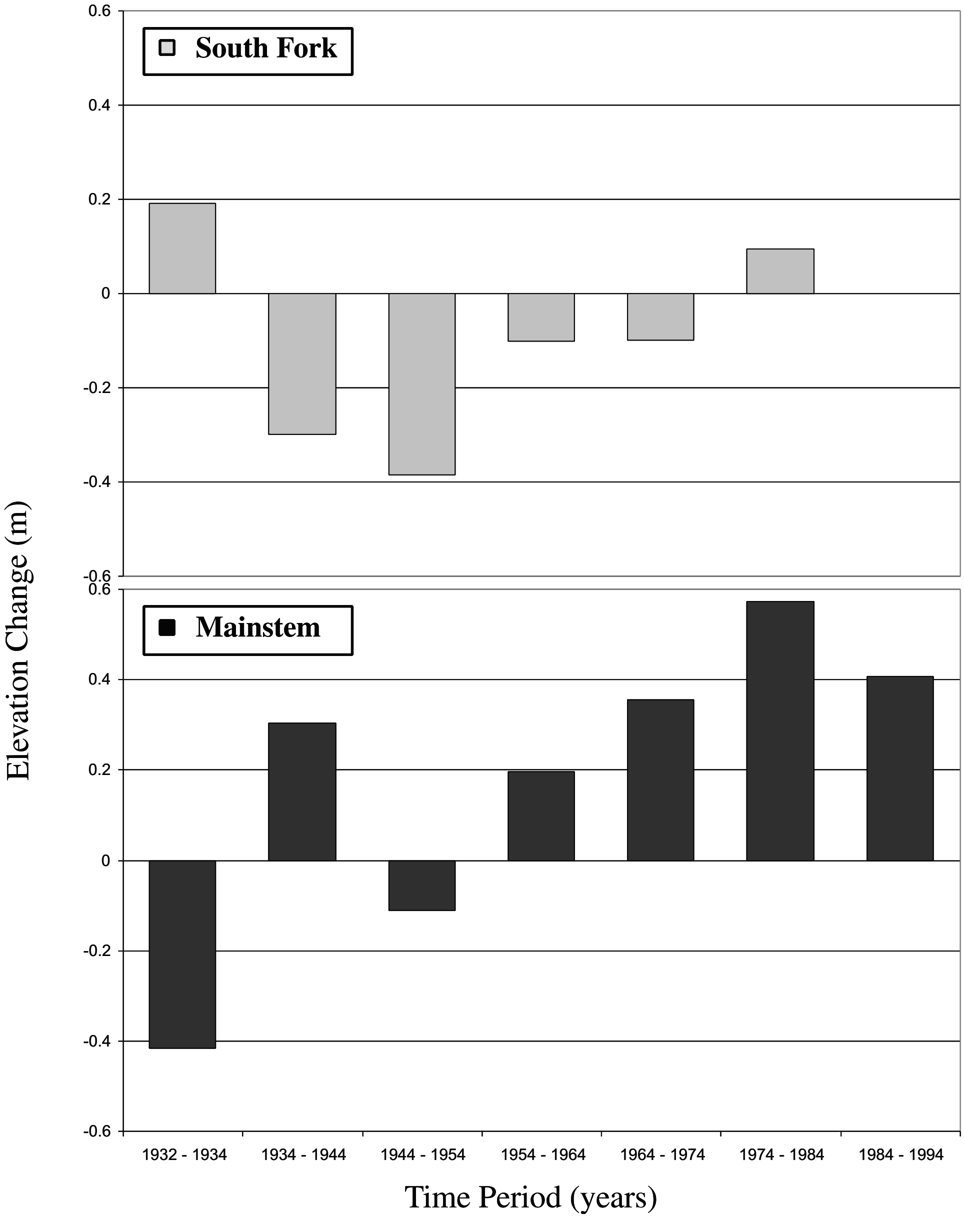

Fig. 10. 1932–1994 aggradation and degradation trends for the mainstem and South Fork reaches, derived from volumetric changes at each reach using Eq. (2). With the exception of 1944–1954, the mainstem aggraded during the South Fork degradation periods.

South Fork and aggradation of the mainstem (Fig. 10) suggests the translation of sediment from the South Fork downstream to the mainstem. For sediment released by degradation of the South Fork and the later sediment pulses in the 1950s to have caused aggradation of the mainstem, a transport rate of 300–660 m/year would be required, which is similar to other reported sediment wave propagation rates of 365–730 m/year (Goff and Ashmore, 1994), 600 m/year (Griffiths, 1979; 1993) and 1000 m/year (Beschta, 1983).

In addition, mainstem aggradation may have been influenced by placement of riprap and natural berm material along the right bank of the channel, upstream of the gaging location beginning between 1971 and 1975 (USGS discharge sheets, various dates). These constraints extend intermittently for nearly 1 km, and served to enhance aggradation and further reduce the mainstem's transport capacity by restricting the ability of the channel to widen in response to increased sediment loads.

7.3. Implications for monitoring programs

Many channel monitoring programs rely on repeated surveys of channel cross-sections for detecting changes in channel geometry. The distinct subannual to multi-year variability apparent in mean bed height trends for both the South Fork and mainstem reaches shows that the interpretation of meaningful trends in mean bed elevations will be strongly impacted by measurement frequency; either frequent measurements or a long record would be required to detect meaningful trends in channel response. For example, annual monitoring of the mainstem Skokomish River from 1958 to 1964 or 1968 to 1976 would not have detected the dramatic ongoing aggradation. Further attention to the design of programs for detecting meaningful trends in channel response from cross-sectional surveys is warranted, especially given the difficulty in sustaining long-term monitoring programs.

8. Conclusions

Our analysis of gaging station records for the Skokomish River indicates that long-term evaluation of trends in both channel morphology and discharge regimes are necessary when examining the effects of land use on flooding. The reduction in the requisite discharge for overbank flow, together with a reduction in the peak discharge regime, shows that recent flooding along the mainstem Skokomish is due to aggradation within the channel. Without significant aggradation of the floodplain, the higher stage associated with smaller discharges allows for a higher frequency of floodplain inundation on the mainstem. Although we have only limited data on land use history, the timing of observed channel changes implies a relationship between land uses and downstream flooding. We suggest that increased sediment loading in the South Fork, combined with a reduced transport capacity from dam construction on the North Fork, resulted in substantial aggradation on the mainstem. The increased flooding along the Skokomish River due to loss of channel conveyance illustrates the importance of considering sediment transport processes and geomorphological change in the assessment and management of flood hazards in forested mountain drainage basins.

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