Long-Term Influence of Jams and LWD Pieces on Channel Morphology, Carnation Creek, B.C.

by

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Abstract

The importance of large woody debris (LWD) pieces and jams on channel morphology and aquatic habitat is reflected by the growth in research in this area that has occurred in the last thirty years, especially in the Pacific Northwest. Despite a long history of research, relatively little attention has been paid to the spatial and temporal effects of jams on channel morphology. Twenty-eight years of cross-sectional surveys (1971-1998) and two extensive longitudinal profile surveys (1991 and 1999) document the influence that jams have on channel morphology at Carnation Creek, B.C. Dramatic changes were observed upstream of a recently formed jam, which included bankfull width increases as much as 178% and sediment accumulation that resulted in decreased mean depths and, in some cases in-channel elevation exceeding bank elevation by 0.5 m.

Jam-related changes in channel morphology were found to occur throughout the longitudinal profile of the stream. Variation of LWD volumes, bankfull width, stream gradient, sediment size and in-channel sediment storage were found to increase with proximity to jams. This variation not only depends on jam presence and position within the channel but also on jam age, with younger jams having the greatest influence on these morphologic parameters. A novel approach using cumulative departure plots successfully identified zones of aggradation and degradation; these zones were in large part determined by jam functioning in each of the zones.

LWD characteristics between the two longitudinal profile surveys changed, reflecting the trend to larger size classes in LWD diameter and length. Changes in jam characteristics as a result of jam aging between the two surveys periods were identified. A period of jam 'conditioning' was identified as being an essential determinant in the overall influence of a jam on channel morphology. As a result of the aging process jams have a tendency towards

decreased influence on channel morphologic parameters, which is primarily due to a reduction in sediment retention ability with time. LWD was present in at least 88 % of the pools in Carnation Creek, with jams being proximate to greater than 65 % of the pools.

An analysis of residual depths was undertaken to examine variation in channel thalweg elevation. Variation between 1991 and 1999 was found to occur at smaller scales than previously reported.

This study further elucidates the spatial and temporal co-evolution of LWD jams and channel morphology. Inferring channel forming events based on the ages of jam structures may prove to be a useful tool when attempting to design forest road crossings in areas with inadequate peak flow records. An understanding of the spatial and temporal nature of jams may also aid in the design and implementation of in-stream restoration projects in anthropogenically and naturally disturbed systems.

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Introduction

General

Large woody debris (LWD) in forested streams occurs as either individual pieces or in accumulations of pieces (jams) and has been the subject of considerable research over the last thirty years. However, relatively little attention has been given to the spatial and temporal dynamics of LWD and, in particular, to how these dynamics are manifested in terms of channel morphology. In order to improve our current understanding of these effects, this study investigates the spatial and temporal nature of LWD with specific attention to jams and the effect that jams have on various channel morphologic parameters.

Clarification of jams and their influence on channel morphology is of particular importance because of the relevance to various engineering applications. For example, in the Pacific Northwest LWD pieces and jams are important components of aquatic habitat, thus the re-introduction of LWD and jams has become a popular tool in the restoration of anthropogenically and naturally disturbed systems (Gippel *et al.*, 1996; Hilderbrand *et al.*, 1998). In addition, the fluvial transport of LWD can pose a threat to forest road crossing structures and is a common reason why these structures fail. An understanding of the spatial and temporal nature of LWD pieces and jams will not only aid in development of more effective restoration projects, but will allow forest managers to better design forest road crossing structures to accommodate the passage of LWD.

The study has three general goals. The first is to assess the conceptual model of channel and jam evolution developed by Hogan (1989) at a finer temporal scale than was previously possible. The second is to assess the influence of LWD pieces and jams on specific channel morphologic parameters. The third is to append the model of Hogan (1989) given the findings herein.

Literature Review

Before the early 1970's, the effects of LWD on the morphology and ecology of forested streams were poorly understood. LWD was considered detrimental to anadromous fish and an impediment to navigation and log transportation. Removal of in-stream LWD was encouraged to improve water conveyance and lessen the risk of damage to bridges and other in-stream structures (Bilby, 1984; Sedell and Frogatt, 1984; Gippel, 1995). Until the mid 1980's, forestry operations in the Pacific Northwest frequently involved extensive stream clearing or removal of in-stream LWD after harvesting in the riparian zone (Maser and Sedell, 1994).

Since the 1970's, the role of LWD in regulating channel morphology (Heede, 1972; Swanson *et al.*, 1976; Keller and Swanson, 1979; Hogan, 1987; Robison and Beschta, 1990; Nakamura and Swanson, 1993; Montgomery *et al.*, 1996), sediment transport and storage (Beschta, 1979; Mosley, 1981; Megahan, 1982; Smith *et al.*, 1993), and aquatic habitat (Bilby and Likens, 1980; Bryant, 1983; Tschaplinski and Hartman, 1983; Lisle, 1986a; Bisson *et al.*, 1987; Hartman and Scrivener, 1990) has been extensively studied, with many of these studies focusing on coniferous riparian forests of the greater Pacific Northwest.

LWD is commonly defined as any piece of wood, including tree stems, rootwads (either attached to stems or not), and large branches, with a minimum diameter ranging from 0.05 m to 0.15 m and a length greater than or equal to 0.5 m (Harmon *et al.*, 1986; Maser and Sedell, 1994; Hogan and Bird, 1998). As previously stated, LWD occurs as either individual pieces or in accumulations of pieces, although LWD is more commonly found in accumulations (Nakamura and Swanson, 1993).

A number of terms have been used to describe accumulations of debris, and despite inconsistencies in definition their usage is common (Bilby and Likens, 1980; Lisle, 1986a; Hedin *et al.*, 1988; Smock *et al.* 1989). Most of the confusion arises from the use of LWD 'dams' and LWD 'jams' to describe accumulations of LWD. Bilby and Likens (1980) described a 'dam' as an accumulation of LWD consisting of at least one relatively large piece, or key-member, with smaller pieces associated with it. Lisle (1986a) labelled accumulations of LWD that spanned the channel as 'dams'. Although the term 'LWD accumulation' is frequently associated with the *active*, *complete*, and *partial* dam types recognised by Gregory *et al.* (1985) and Gurnell and Sweet (1998), no definition of what constitutes the number of pieces of LWD required for a dam is given. From these definitions of dam type, however, it can be inferred that a single log that is at the least a partial barrier to water and sediment movement would be identified as a 'dam'. Hedin *et al.* (1988) referred to 'dams' as any piece of LWD, most often a single log, which spanned the channel and accumulated sediment behind. Additionally, Smock *et al.* (1989) defined a 'dam' as any piece of LWD greater than 5 cm in diameter in contact with sediment and that spanned at least one-quarter of the channel. Clearly, neither the Hedin *et al.* (1988) nor the Smock *et al.* (1989) definitions of a dam describe an accumulation of LWD.

The use of the term 'jam' to describe an accumulation of debris is used more consistently in the literature than 'dam'. LWD that accumulates on the key member(s) piece(s) may develop into a jam if the accumulation consists of at least five key member pieces (Nakamura and Swanson, 1993). Beechie and Sibley (1997) defined jams as accumulations of five or more clustered LWD pieces, without the previous 'key-member' restriction. The term 'jam' was also used to define an accumulation of LWD that consisted of multiple, interacting pieces of LWD that influenced channel morphology (Hogan and Bird, 1998). Accumulations that consisted of high concentrations of LWD were more likely to develop into jams than those comprised of low LWD concentrations (Bryant, 1980).

Whereas 'dam' has been used interchangeably in the literature to describe both accumulations and individual pieces of LWD, 'jam' has consistently been used to describe accumulations of LWD. For the remainder of the literature review the use of the term 'jam' will be used to describe accumulations of LWD that have been clearly defined as such by the author(s). The term 'dam' will be used when the definition includes either single pieces of LWD or is unclear.

Previous research has cited the importance of dams and jams in modifying channel morphology (Heede, 1972; Swanson and Lienkaemper, 1978; Keller and Tally, 1979; Gurnell and Sweet, 1998) and noted that jam-related morphologic changes are usually much greater than changes associated with individual LWD pieces (Nakamura and Swanson, 1993). In some instances, characteristically bedrock reaches upstream of channel spanning jams have evolved into alluvial reaches given adequate sediment supplies (Montgomery *et al.*, 1996). For coastal streams of British Columbia, Hogan *et al.* (1998) concluded that jams are the primary control on channel morphology and aquatic habitat, with individual LWD pieces being important controls between jams.

Variations in the spatial distribution of LWD dams and jams within stream systems depend on stream size, forest type, rates of decomposition, riparian disturbance mechanisms, and the extent of human activity in the watershed (Harmon *et al.*, 1986; Robison and Beschta, 1990; Church, 1992; Gregory and Davis, 1992). Likens and Bilby (1982) and Robison and Beschta

(1990) noted a decrease in the frequency of jams with increasing channel width. Hogan *et al.* (1998) found that spacing of LWD jams, over a range of channel sizes, varied with forest disturbance history, and specifically, that spacing was slightly greater in logged (0.26 jams per channel width) than in unlogged watersheds (0.22 jams per channel width). Conversely, Lisle (1986a) found that jam spacing was considerably higher in forested streams (16 jams/100 m) compared to clear-cut streams (4.2 jams/100 m). Swanson *et al.* (1984) also observed differences in the frequency of accumulations and noted that jams that spanned more than two-thirds of the channel width occurred less frequently than those jams that spanned less than two-thirds of the channel width.

The effects of dams and jams on channel morphology have been extensively studied. Studies have found that dams and jams can influence channel morphology spatially by altering: (1) the flow of water and in-stream hydraulics (Mosley, 1981; Marston, 1982; Megahan, 1982; Gregory *et al.*, 1985; Lisle, 1986b; Abbe and Montgomery, 1995; Gippel *et al.*, 1996); (2) the transport and storage of sediment and organic matter (Swanson, *et al.*, 1976; Beschta, 1979; Mosley, 1981; Likens and Bilby, 1982; Hogan, 1987; Fetherston *et al.*, 1995; Keller *et al.*, 1995; Wallace *et al.*, 1995; Montgomery *et al.*, 1996; Rice and Church, 1996); and (3) the alteration of channel morphologic parameters (Keller and Swanson, 1979; Keller and Tally, 1979; Sullivan *et al.*, 1987; Nakamura and Swanson, 1993; Thompson, 1995; Gurnell and Sweet, 1998). Mosley (1981) and Marston (1982) independently observed that jams and dams altered the flow of in-channel water by acting as in-stream obstructions. Furthermore, Marston (1982) observed that impervious dams impound water during peak flows resulting in increased head and dissipation of potential stream energy. Other authors have observed that LWD jams dissipate potential stream energy as a result of the drop in elevation between locations upstream and downstream of a jam

(Keller and Tally, 1979; Keller and Swanson, 1979). Gregory *et al.* (1985) observed that dams decrease average flow velocity by increasing channel roughness, however this affect decreased with increased flows. They further found that channel spanning dams (*active* or *complete* dams) led to increased frequency of overbank flooding during peak flow events (Gregory *et al.*, 1985). Gippel *et al.* (1996) also noted that flooding frequency is increased at locations upstream of a channel blocking dam because the water level is greater for a given discharge than without the jam. Lisle (1986b) noted that large obstructions, such as LWD jams, cause intense secondary circulation that directs channel bottom velocities away from the obstruction. Finally, Abbe and Montgomery (1996) analysed flow hydraulics around a jam and observed flow constriction and acceleration near the obstruction and flow separation and deceleration downstream.

Eventually the presence of a LWD dam or jam and the associated alteration of in-stream flows and hydraulics result in changes in the bedform characteristics around a dam or jam, and ultimately to changes in the transport and storage of organic matter and sediment. Sites of storage for organic matter and sediment are created in areas of low shear stress upstream of jams where the material can be stored (Fetherston *et al.*, 1995). Likens and Bilby (1982) observed that jams contain 75, 58 and 20 percent of all in-stream organic matter in first, second, and third order streams, respectively. Bilby (1981) found that jam removal led to an increased effectiveness in the downstream transport of particulate matter. Similarly, Wallace *et al.* (1995) observed that the installation of log dams in a channel segment resulted in the increased retention of particulate organic matter, as well as the increased efficiency with which organic matter was processed within the stream system. The increased efficiency was attributed to an observed decrease in the physical downstream transport of organic matter (Wallace *et al.*, 1995). Mosley (1981) concluded that the transportation of inorganic matter is also controlled to a large degree by LWD loading since LWD jams provide temporary base levels and storage sites where sediment can be detained for long periods of time. Jams accounted for the storage and temporary stabilisation of more than 200 m^3 of sediment in a 120 m reach of an old growth stream in Oregon; higher volumes of stored sediment were associated with closely spaced jam complexes (Swanson *et al.*, 1976). Beschta (1979) estimated that 5250 m^3 of sediment eroded from a 250 m reach during the winter stormflow period following jam removal. Megahan (1982) further observed that LWD dams accounted for 42 percent of the in-stream sediment storage in streams located in the Idaho Batholith. Hogan (1987) and Hogan *et al.* (1998) found that large volumes of sediment were stored upstream of LWD jams. Debris jams were found to strongly influence the longitudinal channel profile sometimes inducing sedimentation in otherwise bedrock reaches (Montgomery *et al.*, 1996). Conversely, other studies have noted that characteristically alluvial reaches downstream of channel spanning jams can be transformed into extensive bedrock chutes (Hogan and Bird, 1998). Rice and Church (1996) concluded that complex longitudinal changes in grain size resulted from the trapping efficiencies of jams. Keller *et al.* (1995) concluded that jam-stored sediment may create a buffer system that modulates the movement of excess bed load through the stream system.

The influence of LWD accumulations on flow hydraulics as well as the transport and storage of sediment is manifested in the alteration of channel morphology. Specifically, the presence of dams or jams can lead to changes in the average condition and variance in channel dimensions. Keller and Swanson (1979) found that the development of a jam increased: 1) upstream channel width; 2) the development of scour holes and mid-channel bars in the vicinity of the jam; and 3) the creation of secondary flow channels. Jams were also found to increase the variability of channel depth (Keller and Tally, 1979). Nakamura and Swanson (1993) observed that variations in channel width and gradient are maximised in jam controlled reaches; areas upstream of jams had large channel widths and low channel gradients, findings previously discussed by Hogan (1987).

In addition to altering channel dimensions, jams have been found to influence channel morphologic units, particularly the spacing of pools and riffles. The pool-riffle sequence forms a fundamental unit in fluvial geomorphology with a characteristic spacing of 5 to 7 channel widths (Leopold and Wolman, 1957; Leopold *et al.*, 1964). A recent review of 16 studies by Gregory *et al.* (1994) found the range of pool-riffle spacing in a variety of channelized and unchannelized streams supported the extensively quoted pool-riffle spacing. However, deviations from this range have been reported in forested channels that contain accumulations of LWD (Gregory *et al.*, 1994). Other studies have found that LWD, as well as other in stream obstructions such as boulders and bank projections, can force pool formation as a result of flow convergence and turbulent velocity fluctuations that scour the channel bed, increasing the frequency of pool spacings (Swanson *et al.*, 1976; Lisle, 1986b). Hogan (1986) also found that pool-riffle spacings were affected by LWD, increasing from 1.32 channel widths in logged streams to 3.51 channel widths in unlogged streams in the Queen Charlotte Islands. However, he concluded that the discrepancy between logged and unlogged streams may be partly related to altered LWD characteristics or could be an artifact of the analytical procedure used (Hogan, 1986). In an extensive survey of streams in coastal Alaska and Washington, Montgomery *et al.* (1995) found pool spacings ranging from 0.21 to 13.20 channel widths, and that pool spacing depended upon LWD loading (expressed as the number of LWD pieces per m^2 of channel), channel type, slope, and width. The smallest pool spacings were found in forced pool-riffle channels (that is channels in which more than half of the pool-riffles are forced by the presence of LWD), and ranged from

0.2 to 3.0 channel widths with the smallest spacings owing to the highest debris loadings (Montgomery *et al.*, 1995). Beechie and Sibley (1997) examined 27 streams in coastal Washington and found pool spacings ranged from 1.7 to 7.2 channel widths. Pool spacing was correlated with the interaction between LWD abundance (number of LWD per meter of channel) and channel slope (Beechie and Sibley, 1997). The presence of LWD dams was also found to reduce pool spacings from an average of four channel widths to two channel widths in the Highland Water watershed in England (Gurnell and Sweet, 1998).

The extent of the spatial influence of LWD accumulations on channel morphology is not only dependent upon their distribution within the channel system, but is also dependent upon the relative size and type of each jam (Gurnell and Gregory, 1995; Abbe and Montgomery, 1996; Hogan *et al.*, 1998). The relative size of each jam is a function of the volume and number of individual LWD pieces which comprise the jam and the overall jam dimensions in comparison to a unit area of channel (Hogan and Bird, 1998). Therefore, the larger the relative size of a jam to the channel, the greater the spatial extent of influence a jam could have on channel morphology.

Two fundamental jam types have been identified by Hogan (1989) and are differentiated based on their relation to valley bottom characteristics. Vertical jams develop in channels that are confined by valley walls or have non-erodible banks, and are characterised by a longitudinal series of debris piles. A stepped longitudinal profile is commonly produced at sites of vertical jams, when the upstream sediment wedge fills the entire channel from bank to bank. Since the channel is unable to migrate around the jam additional debris and sediment piles up in the vertical direction (Hogan and Bird, 1998). Conversely, lateral jams develop in unconfined channels with erodible banks. Thus, the channel is able to laterally migrate around the jam. Increased bank erosion occurs as a result of the channel attempting to move laterally around the jam. Such erosion frequently results in the recruitment of additional LWD from the riparian area (Hogan *et al.*, 1998). As LWD and sediment accumulate upstream of a lateral jam, the jam and resultant sediment wedge grow in the lateral direction. Eventually the jam and its associated wedge are abandoned by the active channel, thus moving the sediment into longer-term storage in comparison to the shorter-term storage within the active channel.

The temporal influence of a jam on channel morphology is highly dependent upon the integrity and longevity of a jam, which in turn are both dependent on biogeoclimatic factors such as tree species, channel geology, and streamflow regime (Hogan, 1989; Rice, 1994; Hogan and Bird, 1998). Jam integrity is a function of the stability of a jam (i.e., the ability of a jam to resist movement as a result of peak flows) and the degree of packing within the jam (i.e., the amount of space in between the individual pieces of LWD that comprise the jam), while jam longevity or permanence is a function of the decay and removal rates of the LWD (Hogan and Bird, 1998). The mode of by which the accumulation is deposited will effect the type of jam that develops (Braudrick *et al.*, 1997). Jams that develop at the terminus of debris flows are generally very stable and have a high degree of packing (Keller and Swanson, 1979; Hogan *et al.*, 1998). LWD introduced by landslides, earthflows, and snow avalanches form jams that are generally not as tightly interlinked and are therefore relatively permeable (Swanson *et al.*, 1976). Gregory and Davis (1992) reviewed 22 papers that investigated accumulations of LWD and found that observed residence times for dams and jams ranged from less than one year to greater than 200 years. Most of the studies observed that dam and jam longevity depended upon stand species, frequency of high flows, and level of watershed disturbance (Gregory and Davis, 1992).

The temporal attributes of individual jams within a stream system reflects a multitude of factors specific to each jam; thus each jam will have a different and unique life history. Because of these variable factors, any given stream system is apt to contain jams in various life stages. Within a stream, jams inevitably break down while, at the same time, new jams periodically form creating a continuum of jam age classes (Swanson *et al.*, 1976; Mosley, 1981; Keller *et al.*, 1995). New jams become potential sediment storage sites because of the reduced stream power upstream of the jam, while older jam sites become potential collection sites of in-stream LWD. Some changes in the numbers of *complete* dams and *partial* dams were related to structural changes of individual dams with time, not simply to the addition of new dams or the breakdown of older ones (Gregory *et al.*, 1985; Gurnell and Gregory, 1995). As a dam ages, the resultant structural changes will lead to changes in the way a dam influences channel morphology (Gurnell and Gregory 1995).

Hogan (1989) found that variation in channel morphologic variables were intricately linked with jam age in old-growth forested and logged streams in coastal British Columbia. Later, Hogan *et al.* (1998) proposed a model of spatial and temporal adjustments in channel morphology in response to the development of jams in small to intermediate sized forested streams. This conceptual model is based on extensive channel thalweg surveys and states that prior to the formation of a jam, channels are morphologically complex. However, after a jam has been established, the channel undergoes fundamental changes, the most severe of which occur during the first decade when the spatial extent of these changes can exceed 100 bankfull widths (w_b) for the largest jams. The severity of the changes results from the effectiveness of the recently formed jams to trap sediment, promoting bank erosion, increased channel widths, reduced gradients, and finer sediment textures upstream of the jam. As a result of the interruption in sediment transport from upstream, the channel downstream of the jam is frequently scoured to a cobble armour layer or bedrock. During the second and third decades after jam formation, the jam begins to deteriorate. Consequently, the jam becomes a less effective sediment trap and the sediment supply to downstream zones increase. In turn, the upstream sediment deposit or wedge is downcut, preferred channels are established, and riparian vegetation begins to colonise the bar and bank surfaces producing a channel that approximates pre-jam conditions. Remnants of the jam may still remain along the channel margin and individual LWD pieces may remain along the bed. The individual LWD may develop into log steps, but generally the importance of LWD pieces on channel morphology and aquatic habitat is manifested at much smaller spatial scales, typically over a distance of a few bankfull widths. Finally, fifty years after initial jam formation, there is very little evidence of the original jam (Hogan *et al.*, 1998).

Study Objectives

The purposes of this study are threefold. First, the interpretation of the results of two extensive longitudinal profiles and 28 annual years of cross sectional data from Carnation Creek, an intermediate sized coastal stream, will be used to determine whether or not jams exert a primary control on channel morphology, with individual pieces of LWD being important in between jams. Second, this study attempt to determine if the spatial and temporal characteristics of channel morphology co-evolve with the life history of jams. Lastly, the model originally proposed by Hogan (1989) will be examined at a finer temporal scale than previously reported because data from Carnation Creek are available at a finer temporal resolution than the Queen Charlotte Islands data set which was controlled by natural disturbance patterns.

Methods

Study Site

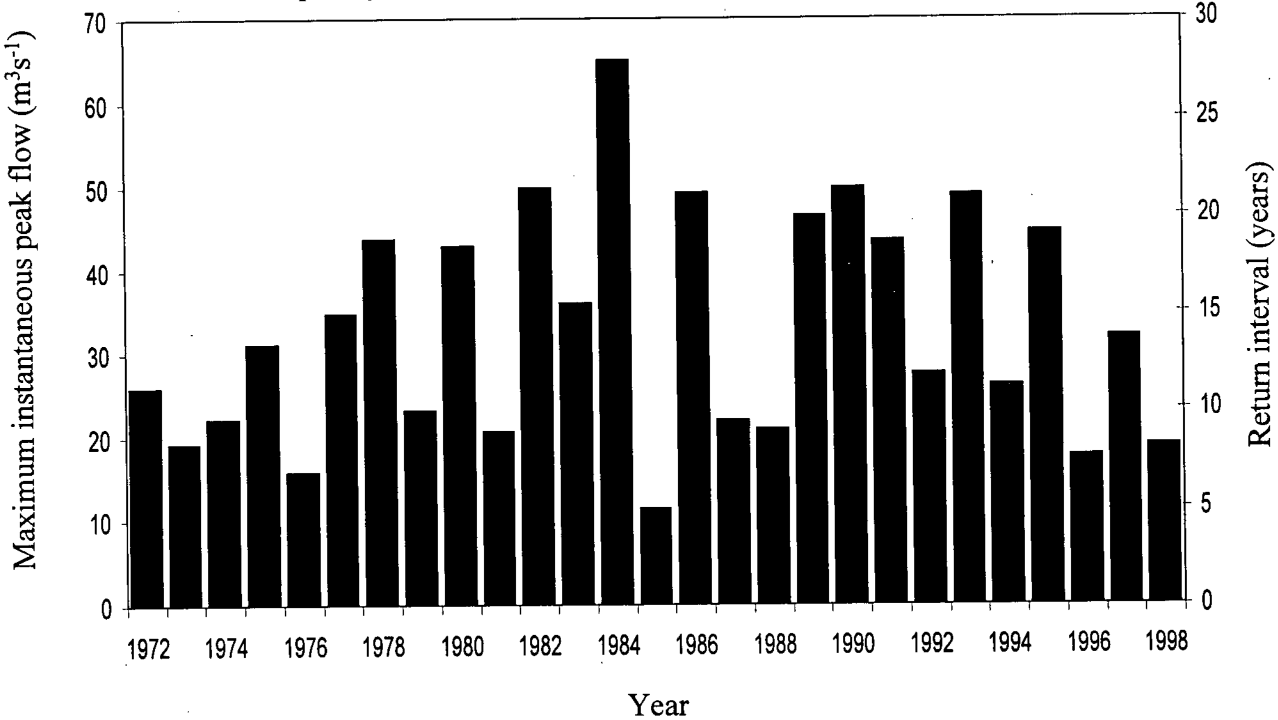
Carnation Creek is located on the west coast of Vancouver Island and drains into Barkley Sound (Figure 1). The 11.2 km^2 watershed has a total basin relief of 800 m; 39 % of the basin topography is steep and irregular, while about 6 % is classed as valley flat (Table 1) (Hogan *et al.*, 1998). Watershed physiography is Estevan Coastal Plain and the dominant geology is Jurassic volcanics of the Bonaza Group (Eastwood, 1975). Carnation Creek is within the Coastal Western Hemlock biogeoclimatic zone. The major tree species of this zone include western hemlock (*Tsuga heterophylla*), amabilis fir (*Abies amabilis*), Douglas-fir (*Pseudotsuga menziesii*), western red cedar (*Thuja plicata*), and Sitka spruce (*Picea sitchensis*). The climate can be described as perhumid, with 95 % of the total annual precipitation (2100 – 5000 mm) falling as rain, 75 % of which occurs between November and March (Hetherington, 1982). Discharge measured since 1971 (Figure 2) spans five orders of magnitude; average daily flow can range from 0.25 $m^3 s^{-1}$ in the summer to 33 $m^3 s^{-1}$ during winter freshets. The largest event on record (occurring in January, 1984) had an estimated instantaneous peak flow of 65.0 $m^3 s^{-1}$, representing a 28-year return interval according to a Gumbel distribution (Figure 2). Carnation Creek can be divided into four zones using channel gradient and valley floor confinement (Figure 3). The first zone contains the upper 2.4 km of the main channel with an average gradient of 0.24 m m^{-1}. In zone 2 the channel flows through a narrow valley flat for 1 km with a gradient of 0.025 m m^{-1}. The next 1 km Carnation Creek, zone 3, is confined by a steep bedrock canyon; the gradient of the channel increases in this zone to 0.085 m m^{-1}. The

Figure 1. Location of Carnation Creek study area

Table 1. Watershed characteristics of Carnation Creek

Characteristic	Carnation
Watershed area (km^2)	11.2
Relief (m)	800
Annual precipitation (mm)	>2100
Physiography	Estevan coastal plain
Percent basin logged:	
Phase I 1976-1981	41%
Phase II 1987-1994	61%

Figure 2. Maximum instantaneous peak flows ($m^3 s^{-1}$) at B-weir in Carnation Creek (numbers on the right), with probable return periods based on the Gumbel frequency distribution (numbers on the left).



lower 3.1 km (zone 4) of Carnation Creek flows through a floodplain which ranges in width from 50 to 200 m and is occasionally constricted by bedrock (Figure 3). Overall, jams that form in this lower section of Carnation Creek can be classified as lateral jams. The floodplain soils consist mostly of gravels and alluvial sands with lenses of sandy-clay and organics (Oswald, 1973).

Figure 3 also shows the locations of the tributary junctions along Carnation Creek. Tributaries C, J, H, and the unnamed tributaries all descend from the valley slopes with gradients ranging from 0.165 to 0.490 m m^{-1}. The other tributaries have gradients generally less than 0.01 m m^{-1} and flow parallel to the main channel before entering it. The relative locations of study areas VII and VIII are also shown (Figure 3).

Carnation Creek is the site of the longest continuing fish/forestry interaction study in a coastal stream ecosystem in North America (Lewis, 1998). Initially, the study design consisted of pre-treatment monitoring (1971-1975), active harvesting during which 45 % of the watershed was logged (1976-1981), and post-treatment monitoring (1981-1986). The project design contained three riparian zone treatments applied in nine study areas, the limitations in the project design have been considered by Lewis (1998). Of the nine study areas, the first eight are located in zone 4 and study area 9 is located in zone 3 (Figure 3). In the first three study areas, or 'leave-strip treatment', an unharvested riparian corridor of variable width was maintained and no in-stream work was permitted (Figure 4). In the second or 'intensive treatment', the riparian zone was logged to the bank and cross-stream yarding was allowed, including the disruption or removal of in-stream LWD (Figure 4). In the third or 'careful treatment', the site was logged to both streambanks but no in-stream work was permitted (for more details about Carnation Creek

Figure 3. Gradient of Carnation Creek and main tributaries as well as the relative locations of study areas VII and VIII. (modified from Hartman and Scrivener, 1990).

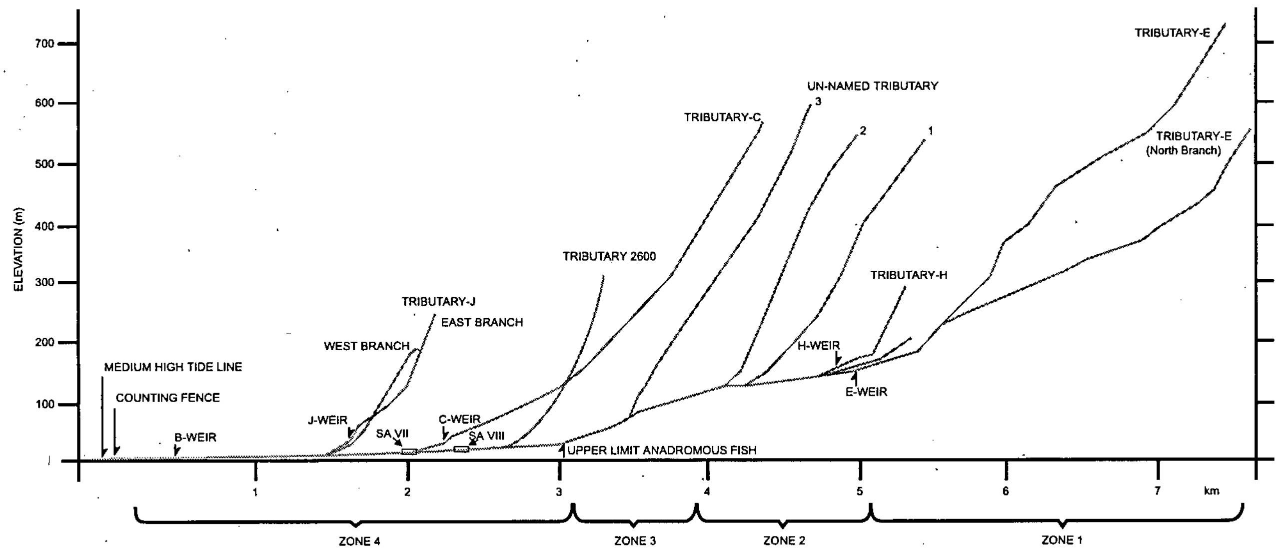
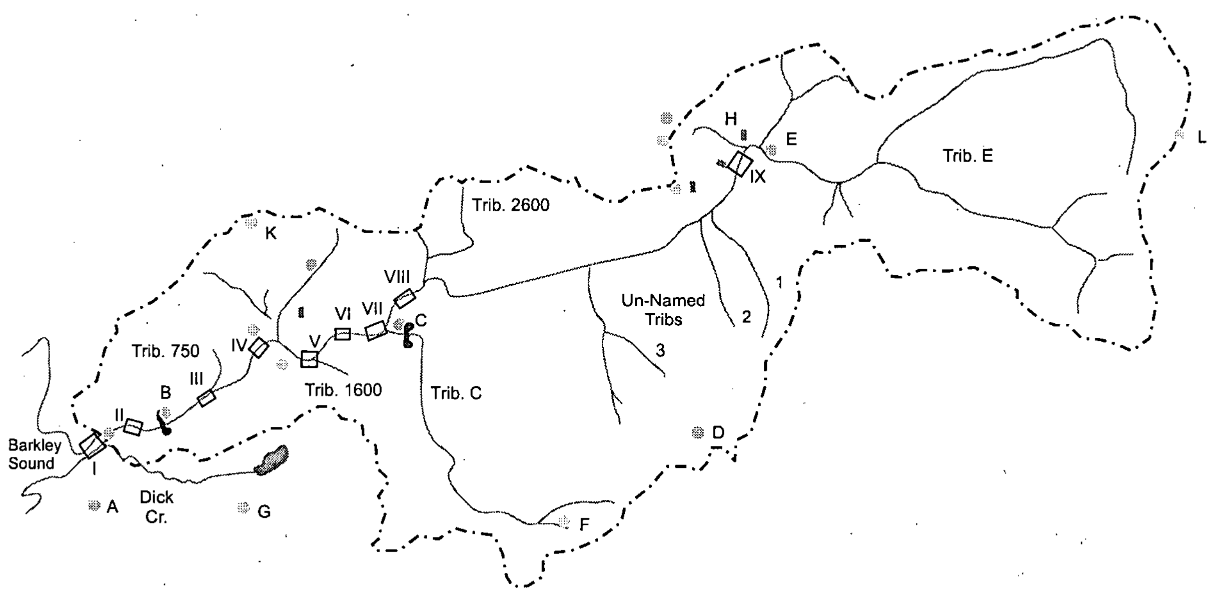


Figure 4. Map of Carnation Creek watershed showing the locations of the nine study areas. (modified from Hartman and Scrivener, 1990).



see Hartman and Scrivener, 1990). The 'careful treatment' study areas were located at the most upstream area of the floodplain, immediately downstream of the canyon. Subsequent logging during 1987-1994 has increased the percentage of watershed logged to 61 %; however, this later logging occurred in the headwaters and was assumed not to have influenced the mainstem of the channel.

Field Data

Cross Sectional Surveys

Field data were provided by the British Columbia Ministry of Forests. Annual cross-sectional channel surveys of Carnation Creek were available from 1971 – 1998 for each of the nine study areas in the fish/forestry project. The study areas were of varying lengths and the channel midline lengths ranged from 45 to 75 m. Cross sections were established at 10 ft (~3 m) intervals within each study area and oriented perpendicular to the channel. In addition to topographic measurements, annual information was gathered on water surface elevation, sediment and vegetation characteristics, and LWD. Of the nine study areas surveyed, only one (study area VIII) will be examined in detail in this investigation, however, some additional information was extracted from selected cross sections in the study area (SA) immediately downstream (SA VII) (Figure 4). SA VIII, located in the 'careful treatment' area, is approximately 50 m in mid-channel length and contains 18 cross sections, each spaced 3 m apart. The site is downstream of the steep incised segment of the creek previously mentioned and is partially constricted by bedrock along the right bank at the upstream and downstream ends. The site will be used to examine the effects of jam formation on channel morphology at a fine temporal and spatial scale. SA VII is located in the 'intensive treatment' area and is 260 m downstream of SA VIII. Of the 18 cross sections located in SA VII, the four uppermost cross sections were used in this investigation to monitor the downstream effects of jam development on morphologic parameters. These four were chosen because a tributary enters Carnation Creek in the middle of SA VII; the four cross sections selected are upstream of the confluence and are not considered to be influenced by the tributary. Annual thalweg lengths for both study areas were calculated as the actual distance between the between subsequent thalweg positions.

In 1991 and 1996, 71 additional cross sections were surveyed in the lower 3.1 km of Carnation Creek between the previously established study areas. The purpose of establishing these cross sections was to monitor morphological changes not previously captured by the existing study areas. On average, these additional cross sections were spaced every two bankfull widths (30 m). In order to complete a continuum of cross sections throughout the lower portion of Carnation Creek, established cross sections within the existing study areas were selected if they coincided with the two bankfull width spacing ($w_b = 2$). The continuum of cross sections was used in this study to estimate mean bankfull width, which was required for analysis. Bankfull width was estimated at each cross section based on morphological characteristics, such as vegetation lines and water marks (Dunne and Leopold, 1978).

Longitudinal Profiles

In addition to the annual cross sectional data, longitudinal thalweg profiles were surveyed in 1991 and 1999 in the lower 3.5 km of Carnation Creek. The length of each survey was 3055 m (203 w_b) and 3060 m (204 w_b), respectively (Table 2). Longitudinal profiles were surveyed using an automatic engineer's level, stadia rod, and surveyor's hip chain, and measurements

Table 2. General characteristics of the two longitudinal profile surveys.

Characteristic	1991	1999
Survey length (m)	3055.0	3060.3
Average channel width (m)	17.07	17.91
Stream gradient (m m^{-1})	0.0100	0.0102
Spacing of measurements		
Channel Width (m)	30	30
LWD (m)	15	15
Volume of LWD (m^3 m^{-2})	0.08	0.08
Percent of total number of LWD		
In jams	76.8	83.7
In pieces	23.2	16.3

were taken in the thalweg at every bankfull width interval (assumed *a priori* to be 15 m) and additionally at every topographic or morphologic break (e.g., pool-to-riffle, step-to-pool, see Hogan and Bird, 1998 for details). The type of channel unit (riffle, run, pool, and glide) was identified at each one of the morphologic breaks. Pools and riffles were delineated according to topographic position, with pools representing topographically low areas and riffles representing topographically high areas (Bisson *et al.*, 1982; Hogan, 1986). Features that could not be clearly identified as either pool or riffle were designated as either glides or runs, both of which are transitional features and represent moderately topographic high areas. Glides are usually located at the downstream end of pools and runs are commonly located at the downstream end of riffles. Average spacing of survey measurements was 5.90 m in 1991 and 4.78 m in 1999. Various other data were collected at the bankfull width interval, including the elevation of the water surface, bar top, bank top, bar extent (Table 3a), b-axis of the largest surface stone visible on the bed (estimated D_{95}), and characteristics of individual LWD pieces and jams.

LWD Piece and Jam Characteristics

LWD characteristics recorded at each survey interval included the diameter, length, and number of pieces per interval, as well as orientation of each piece with respect to channel banks and its relative location within the bankfull channel. The diameter and length of each piece of LWD was visually estimated and independently assigned into one of five size categories (Table 3a). The amount or number of LWD pieces per survey interval (w_b), was also independently split into five classes; these represent the number of LWD pieces within the interval for the same diameter and length class (Table 3a). In addition, the relative orientation of LWD to the channel

Table 3. LWD survey classification system: a) class descriptions used in the surveys to describe the extent of the cross sectional channel width occupied by a bar and for LWD characteristics; b) an example of a survey entry for LWD characteristics.

a)

Rank	Portion of bankfull channel width (w_b) occupied by bar surface	Diameter (m)	Length (m)	Amount (number/w_b)
1	>1	<0.1	1-5	<2
2	¾-1	0.1-0.3	5-10	2-3
3	½-¾	0.4-0.7	10-15	4-7
4	¼-½	0.8-1.2	15-20	7-12
5	<¼	>1.2	>20	>12

b)

Diameter (m)	Length (m)	Amount (#/w_b)	Orientation	Relative Position
1	2	2	perpendicular	Partly
4	2	5	perpendicular	Within
2	3	1	parallel	Partly
5	1	1	diagonal	Within
2	2	2	diagonal	Above

banks was also recorded for pieces of LWD in each diameter and length class. Relative location of each LWD piece within the bankfull channel was defined as being either wholly within the channel (within), partly in and partly above the channel (partly), or entirely suspended above the channel (above) (Table 3b). An example of how the LWD characteristics were recorded in the field is provided (Table 3b). According to the first line of data in Table 3b, there are 2-3 pieces of LWD (amount class = 2) that are less than 0.1 m in diameter (diameter class = 1) between 5 and 10 m in length (length class = 2), oriented perpendicularly with respect to the channel banks, and partly within and partly above the bankfull channel.

For the purposes of this survey, jams were defined as a major accumulation of LWD and/or debris that either currently or historically (where LWD remnants were still evident) alters or recently altered channel morphology and downstream sediment transport (Hogan and Bird, 1998). Information specific to jams was collected according to the classification system of Hogan and Bird (1998). This largely qualitative classification was developed to specifically assess the spatial and temporal response of a stream channel to the development of LWD jams. Information recorded for each lateral jam in Carnation Creek included jam age, size, span, height, channel location, number of channels, shape, and sediment storage associated with the jam (Appendix 1). The information on jam characteristics was collected separate from and in addition to the LWD characteristics measured at each survey interval. Thus, information on the characteristics of the LWD that comprised the jam and the characteristics of the jam itself were obtained.

Aerial Photographs

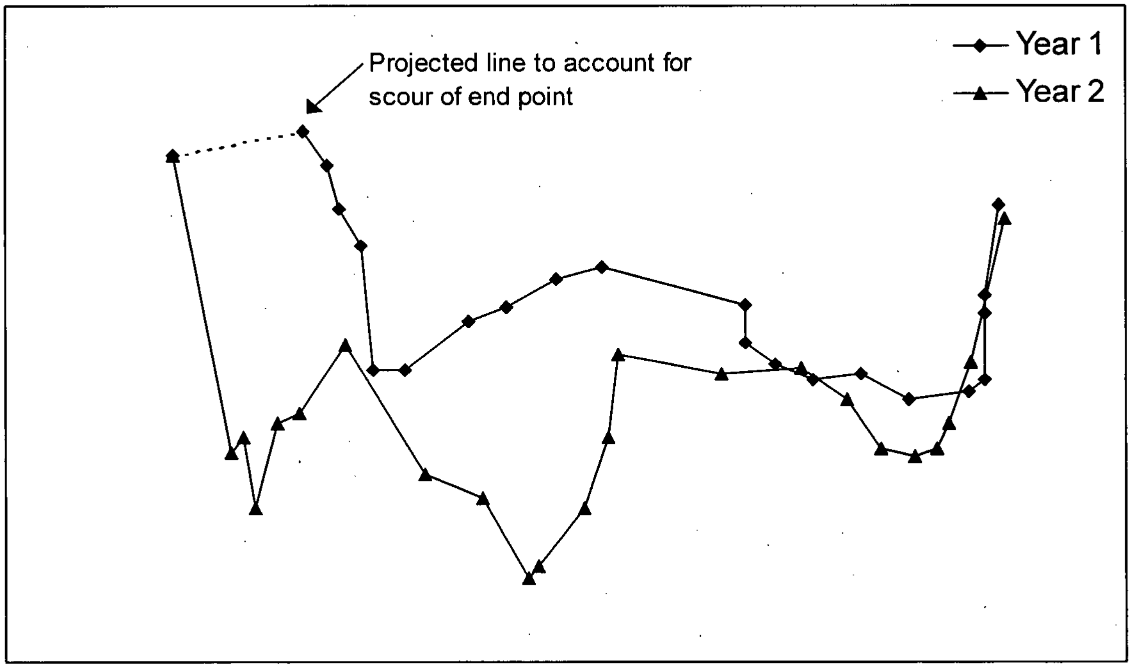
Low level (1:500 - 1:1000) 70 mm aerial photographs of Carnation Creek were obtained from the Ministry of Forests. Twelve years (1977, 1980, 1981, 1982, 1983, 1984, 1987, 1990, 1991, 1992, 1993, and 1997) were used to aid in tracking the development of jams along the lower portion of Carnation Creek. The photographs were also used in piecing together the history of channel change in SA VIII as well as the development and abandonment of a jam lower down the longitudinal profile.

Analytical Techniques

Scour and Fill Data

Scour and fill data were used in addition to other morphologic parameters (bankfull width and bankfull depth) to assess the changes in channel cross sectional area resulting from the presence of a LWD jam. All historical data were carefully and critically reviewed to ensure consistent analysis. If bank tops as identified in the field were at different heights, a horizontal line was projected along the cross section from the lowest elevation bank top to the opposite bank. If no indication of top of the banks was given in the survey notes, the levels from the previous years were used in conjunction with a close examination of the cross section in question. In some instances the end point of a cross section had been scoured out (Figure 5). Before scour and fill could be calculated, the gap between the end point of the cross section in the previous year with the end point in the subsequent year had to be bridged. This was accomplished by projecting the previous year's end points (year 1) to the location of the top of the bank in the subsequent year (year 2) (Figure 5). Bankfull width was determined from the

Figure 5. Diagram illustrating method used to adjust a channel cross section (year 1) to account for bank erosion in the following year (year 2). The area under the dotted line would be calculated as scour.



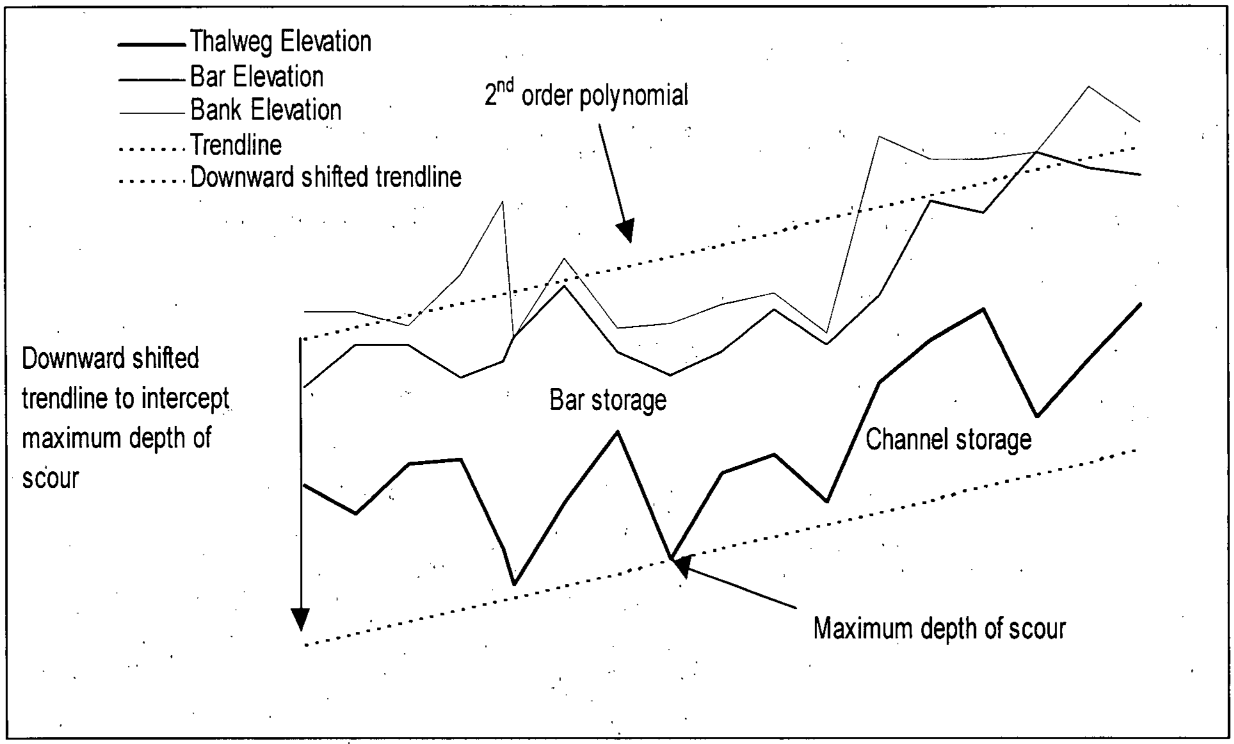
corrected cross section data and the average width of all cross sections was used to represent average bankfull width for Carnation Creek.

In addition to using bankfull width as an indicator of morphologic change, it was also chosen as a scaling factor (e.g., LWD/ w_b). Areal scour/fill measurements of the cross sectional data from study areas VII and VIII were determined using the program SCOUR (Madej *et al.*, 1999).

Bar and Channel Sediment Storage

Sediment storage in bars and in the channel was determined by calculating the cross-sectional area of stored sediment at each longitudinal survey interval. To do this, a second-order polynomial was calculated by using least squares and fit to the bank elevation data (Figure 6). The bank elevation data was chosen because it best approximated the underlying non alluvial topography. Next, the second-order polynomial was shifted downward so that the curve intersected the maximum depth of scour observed along the thalweg, as this depth was assumed to represent the minimum depth to the non-alluvial topography. The cross-sectional area of sediment stored between the thalweg and the underlying topography (i.e., channel-stored sediment) was calculated as the difference between the thalweg elevation and the shifted second-order polynomial (Figure 6). This difference is then multiplied by the channel averaged bankfull width. Bar stored sediment was calculated as the difference between the observed bar elevation and the thalweg. This difference is then multiplied by the recorded bar extent for that specific interval and the average channel bankfull width. Successive cross sections were averaged and multiplied by the length of the survey interval to estimate the volume of sediment stored between each survey interval for both storage types.

Figure 6. Diagram of methods used to calculate channel stored and bar stored sediments.



Channel stored sediment was calculated as the difference between the downwardly shifted trendline and the actual thalweg. In order to obtain sediment volumes this value was then multiplied by average bankfull width. Bar stored sediment was calculated as the difference between the bar elevation data and the thalweg. Bar volume was obtained by multiplying this value by the average bankfull width times the bar extent.

Cumulative Departure Plots

A cumulative residual departure plot for each longitudinal profile (i.e., 1991 and 1999) was constructed to identify zones of sediment degradation and aggradation within the channel. To construct these plots the distance and thalweg elevation data from both survey years were combined and a second-order polynomial was fit to the new combined data set using the method of least squares. It was felt that the equation from the combined data set represented a common reference line from which to interpret the cumulative departures from both surveys. In order to identify points at which sediment storage characteristics change, the cumulative departures (cd) for the 1991 longitudinal profile were computed as

$$\mathrm{cd} = \sum (O_D - P_D) \qquad (1)$$

where O_D is the observed thalweg elevation at a given distance D in the 1991 profile and P_D is the predicted thalweg elevation at the same distance D determined using the second-order polynomial equation derived from the combined data set. The same method was used to determine the cumulative departures for the 1999 survey. It is hypothesised that inflection points and flat areas in the graph identify transitional areas in the channel thalweg between zones of sediment accumulation and sediment degradation. Rises in the graph of cumulative departures represent zones of sediment accumulation in the channel, whereas degradation zones in channel are reflected by declines in the graph of cumulative departures.

LWD Characteristics

In order to understand the spatial distribution of LWD jams along the profile, nearest neighbour analysis was conducted for both survey years (Wing *et al.*, 1999). The mean distance to the nearest neighbour ($\bar{r}_A$) is calculated as:

$$\bar{r}_A = \frac{\sum_{i=1}^{n} r_i}{n} \qquad (2)$$

where r_i is the measured distance to nearest neighbour for jam *i* and *n* is the number of jams in the study area. The expected distance to the nearest neighbour ($\bar{r}_E$) is obtained by:

$$\bar{r}_E = \frac{1}{2}\sqrt{A/n} \qquad (3)$$

where *A* is the study area size, that is survey length times average bankfull width. Pinder and Witherick (1975) modified equation (3) for linear point patterns; the expected distance to the linear nearest neighbour ($L\bar{r}_E$) is:

$$L\bar{r}_E = \frac{1}{2}\left(\frac{L}{n-1}\right) \qquad (4)$$

where *L* is length of the survey and *n* is the number of jams.

The expected and observed mean nearest neighbour distances can be used to construct an index of the spatial pattern of LWD jams. The distribution ratio (*LR*) is defined as:

$$LR = \frac{\bar{r}_A}{L\bar{r}_E} \qquad (5)$$

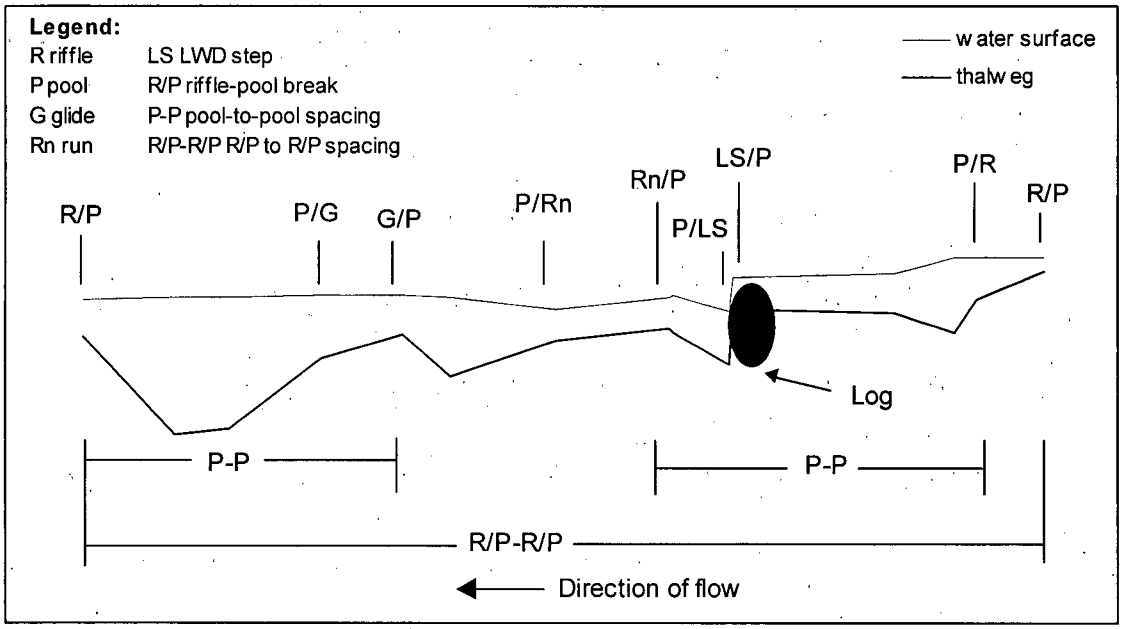
If *LR* equals one then the pattern exhibited by the jams is completely spatially random. An *LR* less than one suggests potential clumping or aggregation, and values greater than one indicate a degree of regularity, or that jam spacing is related to fluvial processes.

The volume of LWD was calculated as the volume of a cylinder using the midpoints of the diameter and length classes (Table 3a). In order to obtain the overall volume per bankfull interval, LWD volume was then multiplied by the mid-point of the number of LWD pieces per interval (Table 3a). Jam volume was determined by summing the volume of all LWD associated with the jam, regardless of whether or not it was within the bankfull channel dimensions.

LWD and Pool Characteristics

The effects of individual LWD pieces and jams on pool spacing and pool characteristics were also explored. The methodology used to assess pool-to-pool and riffle-pool spacings are defined in Figure 7. Note that if a pool (P) was separated by a log step (LS), for example P/LS to LS/P, it was counted as a single pool and not two. To analyse the association between pools and individual LWD pieces and jams, pools were defined as: 'jam proximate' (at least part of the pool is located within one channel width of a jam or the pool is located within one channel width of a jam-related sediment wedge); 'LWD proximate' (at least part of the pool is located within one bankfull width of an individual piece of LWD); free (entire pool was more than one channel width from either the nearest LWD jam or individual piece); or bedrock (entire pool was more than one channel width from either an individual piece of LWD or a jam and was constricted by bedrock for greater than 50 % of its length). This categorisation is modified from the distinction of self-formed and forced-pools by Montgomery *et al.* (1995) and the proximate and free pool definition given by Gurnell and Sweet (1998).

Figure 7. Definition diagram for pool-to-pool spacing and riffle-pool spacing. Actual field data were used to construct this plot.



Residual Pool Depths

Variability in the longitudinal profiles for the 1991 and 1999 surveys was assessed by analysing the distribution of residual depths (e.g., Lisle, 1995 and Madej, 1999). Residual depth is defined here as the difference in elevation between a point in the thalweg and the highest thalweg elevation downstream, given that it is higher than the point upstream (Lisle, 1987). Residual depths were derived from longitudinal profile data using LONGPRO program (Madej and Goforth, 1999). Output from the LONGPRO software yielded a distribution of residual pool depths, including residual pool depth values and zeros for the riffles.

The bed elevations between survey points were linearly interpolated to create a common base from which to compare the two longitudinal profiles. To capture the variability of fine-scale features, such as a log step, a standardised spacing of 1 m was selected. Depressions in the thalweg were defined as being either a pool or scour hole if the maximum residual depth in the depression exceeded 0.1 m (Lisle, 1995). The standardised file was then compared to the field data to verify that the standardised profile reflected the "true" morphology. For the purposes of this analysis pools, glides, and runs were treated as similar, whereas riffles were treated differently.

Variability in bed elevation was then evaluated using the standard deviations of the distributions of residual water depth for each survey year (Madej, 1999). These distributions were tested for normality using the Kruskal-Wallis test. Differences in the medians and distributions of residual water depths between the two survey years were tested using the Mann-Whitney and Kolmogorov-Smirnov tests, respectively.

Results & Discussion

Cross Sectional Data

Introduction

In addition to the boundary characteristics (i.e., erodible or non-erodible) of a channel bed and bank, the shape of a channel's cross section is determined by sediment load, discharge regime and structural elements. Accumulations of LWD can potentially alter all three variables to a certain degree. Therefore, the development of a jam within SA VIII offered a rare opportunity to document change in channel cross sectional shape associated with the jam. Nakamura and

Swanson (1993) were able to document major change in the form of the low-flow channel resulting from individual pieces of LWD and accentuated by high peak flows. Smith *et al.* (1993) documented nearly 0.7 m of aggradation in a 4 m wide channel cross section following the in-stream removal of LWD. LWD removal also resulted in the erosion and undercutting of channel banks, as well as scour and fill in measured cross sections at Larry Damm Creek, California (Keller and MacDonald, 1995). None of the studies were able to document, however, the effects on channel cross section form as a result of a jam. In this section the development of a jam within SA VIII will be analysed.

Qualitative Analysis of the Effects of Jam Development on Channel Morphology

Study areas VII and VIII provided an opportunity to examine the effects of jam development on channel morphology during a 27 year period. Morphological maps and the low elevation aerial photographs were used to develop a qualitative account of changes in SA VIII.

A quantitative assessment of channel changes will be presented in the next section and is based on sequential channel cross-section analysis including SA VII. Figure 8 (morphological maps of 1972, 1977, 1979, 1982, 1984 and 1991) shows the survey maps for SA VIII. A large log spanning the channel is evident in the 1972 map (Figure 8a). The log is perpendicularly oriented upstream of survey hub R-50-A. There is evidence of sediment accumulation upstream of the log, as well as some LWD in the channel loosely associated with the key piece (represented in the figure by cross-hatching). The majority of the reach was classified as pools, with individual pieces of LWD forcing 6 of the 7 pools located in the reach. In the 1977 map, more LWD is present in the channel as logging activities increased upstream of SA VIII (Figure 8b). The log present in the 1972 map became a key member piece of a jam in the 1977 map by effectively trapping debris. From low elevation aerial photographs taken in 1977, it was evident that the gravel bar in the 1977 map was not due to the jam located in SA VIII, but was part of a sediment wedge related to a jam located immediately downstream (Figure 9a).

SA VIII was logged in 1979 and substantial amounts of logging-related debris were already in proximity to the anchor log (Figure 8c). The addition of a new key member is also evident in the 1979 map (Figure 8c). The accumulated sediment evident in the map is related to the jam downstream of SA VIII, which also grew in size following logging, as revealed in the photographs. Additionally, an advancing side bar can be seen entering SA VIII in the 1981 photograph, located at the upstream end of the reach along the right bank (Figure 9b). In the 1981 photograph the jam immediately upstream of SA VIII was also altering sediment transport patterns in addition to the growing influence of the jam within SA VIII (Figure 9b). The size of the jam has greatly increased since the 1977 photograph (Figure 9a).

Figure 8. Morphological maps of study area VIII for: a) 1972, b)1977, c)1979, d)1982, e)1984, and f)1991.

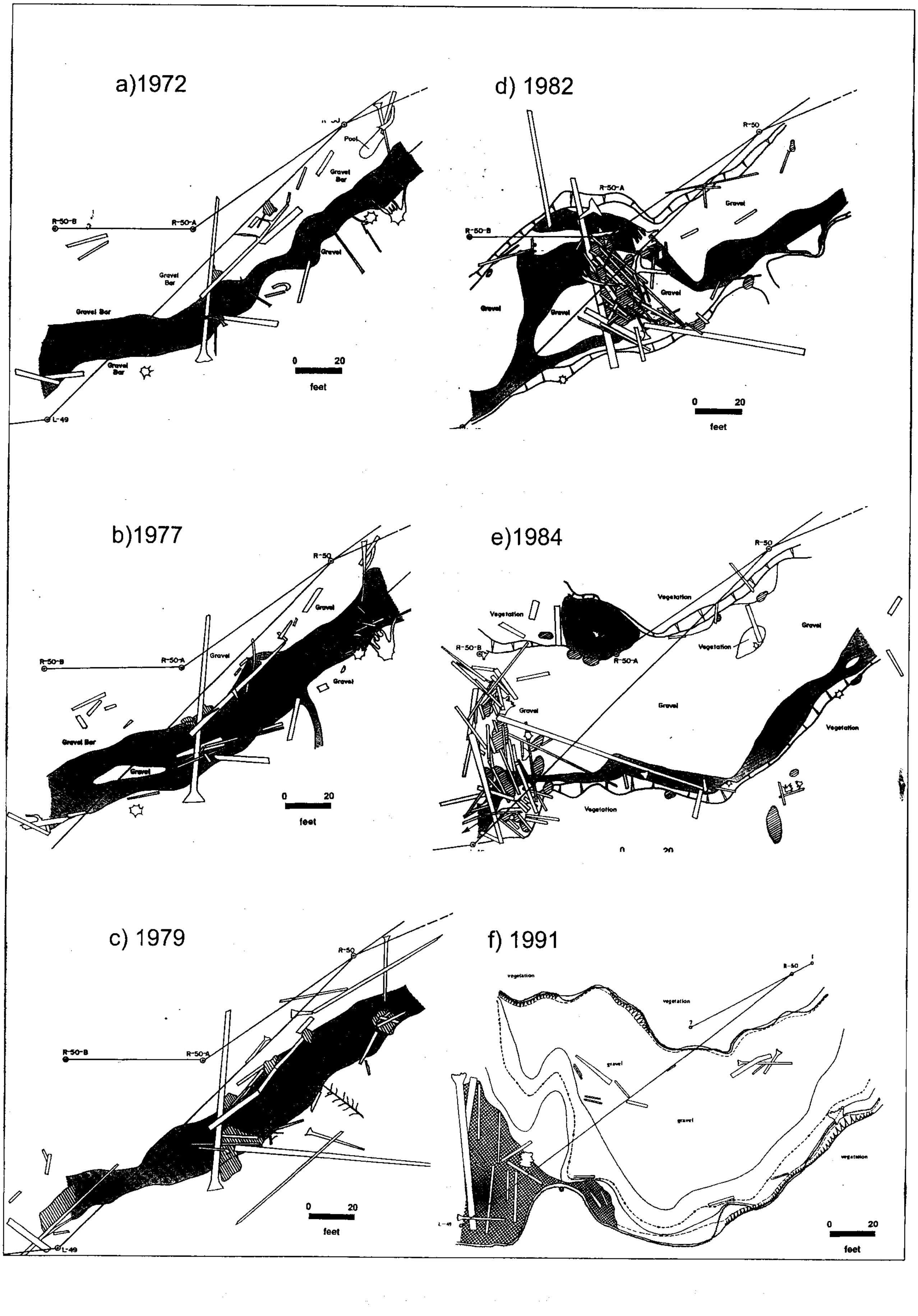
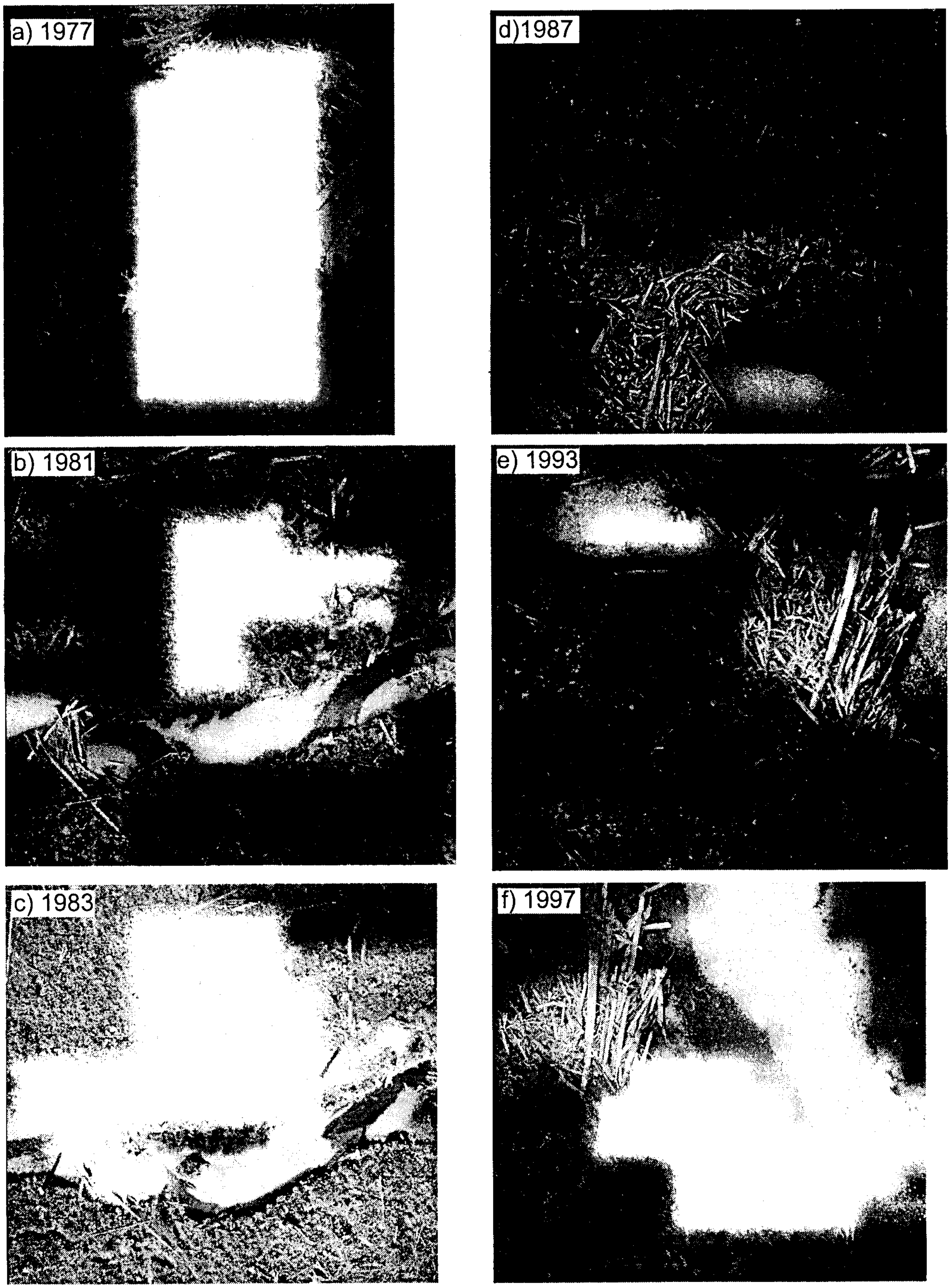


Figure 9. Low-level aerial photographs of SA VIII for: a) 1977, b)1981, c)1983, d)1987, e)1993, and f)1997.



Due to jam 'conditioning' that resulted from the 1982 peak flow event, the jam within SA VIII became a partial barrier to sediment transport (Figure 8d). Conditioning of a jam describes the structural changes that a jam undergoes that increase its effectiveness in altering local hydraulics and sediment transport. Examples of 'conditioning' changes include decreased void spaces within the jam structure and increased area of interface between the jam and active channel. The result of jam 'conditioning' is the sediment accumulation upstream of the jam along the left bank, which led to channel widening (Figure 8d). The sediment wedge associated with the jam downstream of SA VIII was being downcut as a result of the flow diversion due to the jam as well the increased scour potential of the sediment starved flows downstream of the jam in SA VIII. These features can be clearly seen in the 1983 photograph (Figure 9c). A large scour hole developed on the right side of the channel due to jam-induced flow convergence; this scour hole is evident immediately upstream of the jam and along the right bank (Figure 9c). The additional LWD that accumulated on the jam as a result of the 1982 storm is also seen in the 1983 photograph (Figure 9c).

In 1984, the characteristics of the jam were significantly altered by a debris flow triggered by a large rain event and a partial collapse of the upstream canyon (Figure 8e). The debris flow moved the jam, intact, approximately 20 m downstream adding significant amounts of both debris and sediment (Powell, 1988). The movement of the material further downstream was halted by the previously mentioned jam located immediately downstream of SA VIII; the downstream jam was anchored by a key-member with its rootwad still attached. The effect of the debris flow on the jam was further 'conditioning', that is it packed both debris and sediment together forming an almost impermeable barrier to both sediment and water. The 1984 map shows the new location of the jam in relation to the SA VIII reach; the jam extends downstream past the map boundaries (Figure 8e). The resultant sediment deposited upstream of the jam is the dominant morphological feature in SA VIII. A deep pool is identified in the 1984 map in the location of the previously discussed scour hole. The channel is now restricted to flow along the left bank by the sediment wedge (Figure 8e). The advancing side bar was also buried as a result of the debris flow.

By 1987, the sediment wedge dominated the morphology of the channel within SA VIII. The wedge buried upstream riffles and pools, and partially filled the scour hole on the right side of the channel (Figure 9d). A large portion of the channel was dewatered during low flows as baseflow was rerouted through the sediment wedge. In the low-level photographs the jam does not appear to have as high of an integrity in 1987 as it had in the 1983 photograph; the 1987 photograph was taken during high flow (Figure 9d). Movement of individual pieces within the matrix of the jam may have resulted from the 1986 peak flow event (Figure 2). The development of flood channels on either side of the jam indicates the impoundment and subsequent over topping of the banks during peak flow events, both of which are evident on either side of the jam in the 1987 photograph (Figure 9d). The channel remained relatively unchanged until the 1990 peak flow event (Figure 2), the results of which can be seen in the 1991 morphological map (Figure 8f). The channel scoured into the upstream wedge along the left bank after it had broken through the jam on the right side taking part of the jam with it.

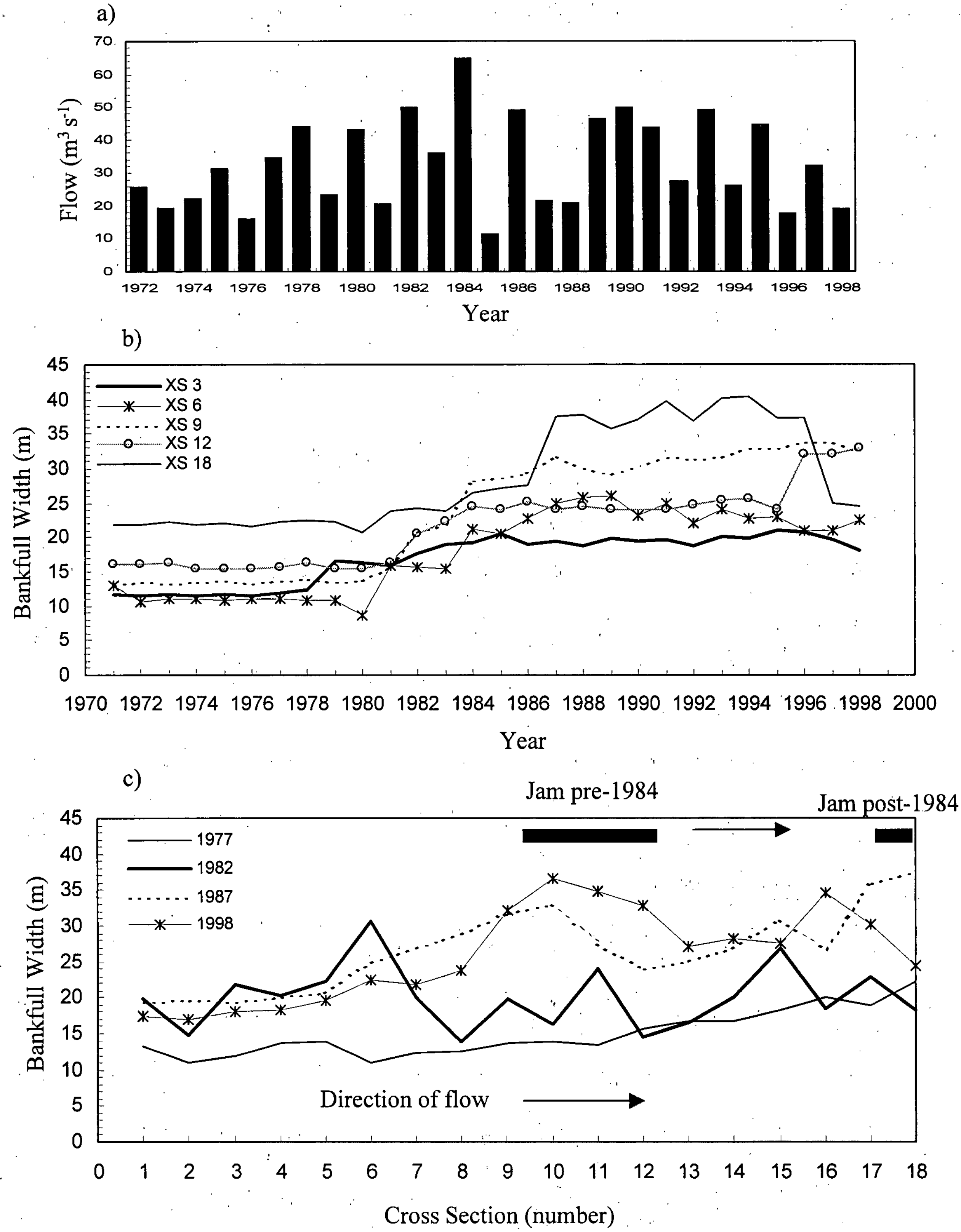
The jam was further reduced in size after the 1991 winter flows (Figure 8f). The ability of the channel to completely migrate around the jam on the right side of the channel is prevented by a bedrock outcrop. The upstream half of the jam is seen in the 1993 photograph, gravels accumulated downstream of the structure are evidence of the current downcutting of the upstream wedge (Figure 9e). Subsequent downcutting of the wedge has led to the isolation of the jam on the left bank. By 1997 the jam only interacted with the channel during high flows and the majority of the wedge remained along the right bank (Figure 9f). The wedge is now sparsely vegetated with alder and spruce.

Quantitative Analysis of the Effects of Jam Development on Channel Morphology

The co-evolution of the jam and channel morphological parameters can be traced through time quantitatively, given the annual cross sectional surveys. Four periods of jam development at SA VIII have been identified in order to facilitate analysis: 1) pre-jam phase: 1971 - 1977; 2) jam adolescence: 1977 – 1983; 3) jam maturity phase: 1984 – 1989; and, 4) jam senescence: 1990 – present. In the annual cross-sectional profiles, at least one year was selected that best represented each of the final three development periods. For the pre-jam phase most of the morphologic variables used for analysis were very similar from 1971 until 1977, so 1977 was selected. Five of the 18 SA VIII cross sections (XS) are selected for the sake of clarity, as illustrative examples. XS 3, 6, and 9 were located upstream of the key member and subsequent jam during the entire survey period (Figure 10b). XS 12 was within the jam until 1984 when the structure moved downstream, and XS 18 was downstream of the jam until 1984. Each of the cross sections were selected based on their representativeness of variabilities within the cross sections of SA VIII. For the four cross sections selected in SA VII, the year selected focused on presenting the annual variability within the cross sections.

Bankfull widths for the selected cross sections and reach averaged widths for selected years in SA VIII are shown in Figure 10 (the additional data for the entire SA VIII section: XS1-XS18 and SA VII: XS1-XS4 for all variables discussed in this section are presented in Appendix

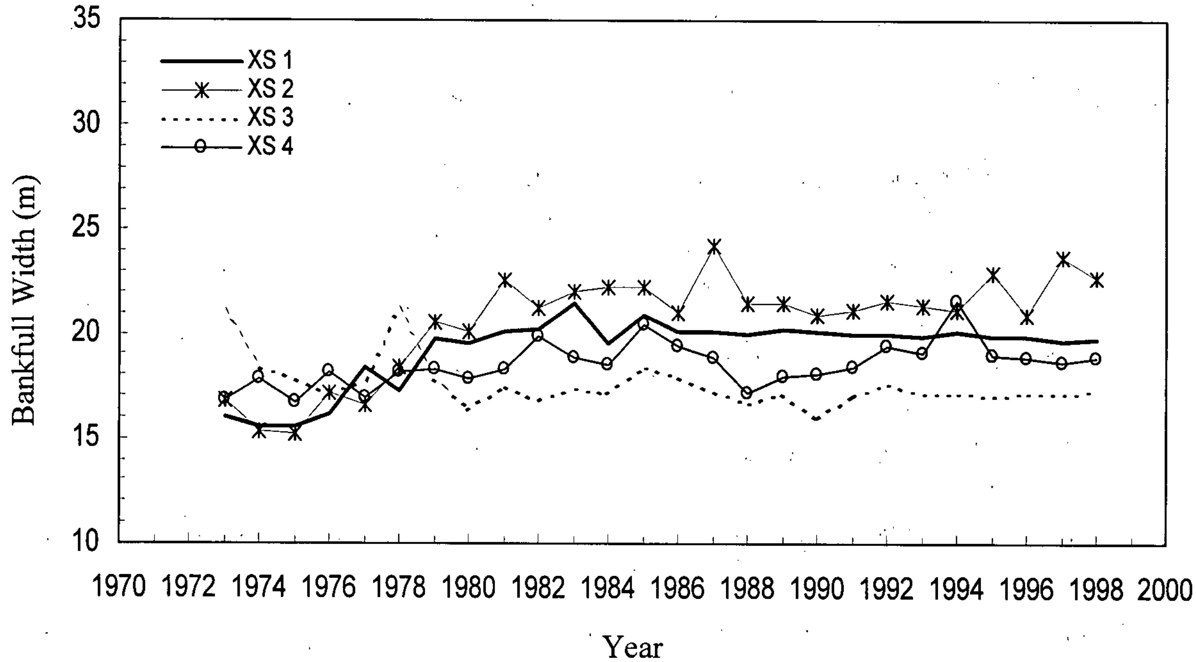
Figure 10. Bankfull widths from study area VIII: a) flow data from Figure 2; b) bankfull widths (m) for the selected cross sections; and c) average bankfull widths for selected survey years. Bankfull widths of the selected survey years were obtained by taking the average bankfull width of all 18 cross sections in study area VIII for the year shown. Cross sections are spaced at 3 m intervals, with XS 1 at the upstream end. The jam location prior to 1984 and post 1984 is also given in c).



2). A persistent pattern of increased bankfull widths for all of the cross sections is observed in 1982, especially XS 9 and 12. XS 9 and 12 were in close proximity to the jam in 1982 and therefore would exhibit jam-induced changes immediately (Figure 10a). The onset of the changes in 1982 coincided with the structural changes in the jam brought about by increased debris in the system after logging and the peak flow event in 1982 (Figure 10a). The 1984 peak flow event and debris flow led to dramatic changes in bankfull widths (Figure 10b). Changes in bankfull width at XS18 did not occur until the next peak flow event in 1987. It is hypothesised that bankfull flows were diverted around XS 18 through side channels, which can be seen clearly in the 1993 aerial photographs (Figure 9d). The development of the sediment wedge in 1984 reduced the channel's capacity to support even moderate baseflows. This led to frequent overbank flooding and the eventual development of side channels. These side channels may have acted to dissipate stream energy, thus delaying the width changes in XS 18 until the 1987 storm event in which their capacity was exceeded.

Annual plots of changes in bankfull width are shown in Figure 10b. The variability of widths exhibited in SA VIII is relatively small in 1977 ($\bar{x}$ = 14.95 m, σ = 3.23) when compared to the later years (Figure 10b). The development of the jam by 1982 initiated a shift in the overall bankfull width for SA VIII ($\bar{x}$ = 18.15 m, σ = 3.76), which can be seen by comparing the 1977 and 1982 plots (Figure 10b). In 1987 ($\bar{x}$ = 26.65 m, σ = 5.63), three years after the downstream shift of the jam, reach averaged width had increased 75 % since 1977 and width variability within the reach had increased by more than 74 % since 1977. The lingering influence of jam development in SA VIII is still evident in 1998 ($\bar{x}$ = 25.96 m, σ = 6.57) with average bankfull widths still 10 m greater than pre-jam (1977) levels. The presence of the jam in SA VIII has lead to an average 5 m increase in bankfull widths for each of the cross sections. In

Figure 11. Bankfull widths for the four selected cross sections of SA VII.

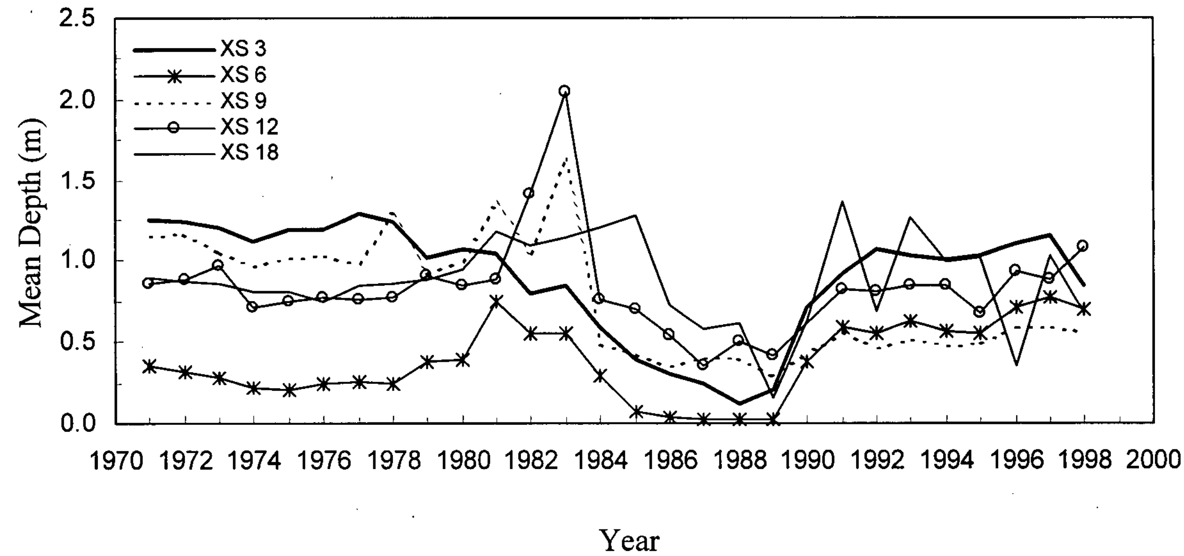


SA VII neither the presence of the jam nor the effects of the 1984 peak flow event and debris flow had an effect on bankfull width (Figure 11). This evidence supports the notion of the downstream 'buffering' ability of jams; the SA VII cross sections were relatively unscathed following the 1984 peak flow event despite the large flow volumes and the volume of debris and sediment deposited in the channel during these events. However, the changes in bankfull width downstream of a jam are not expected to be as severe as those upstream of a jam. Overtime, as the upstream supply of sediment is reduced, the downstream channel may begin to narrow as vegetation becomes established along the margins of the bar tops.

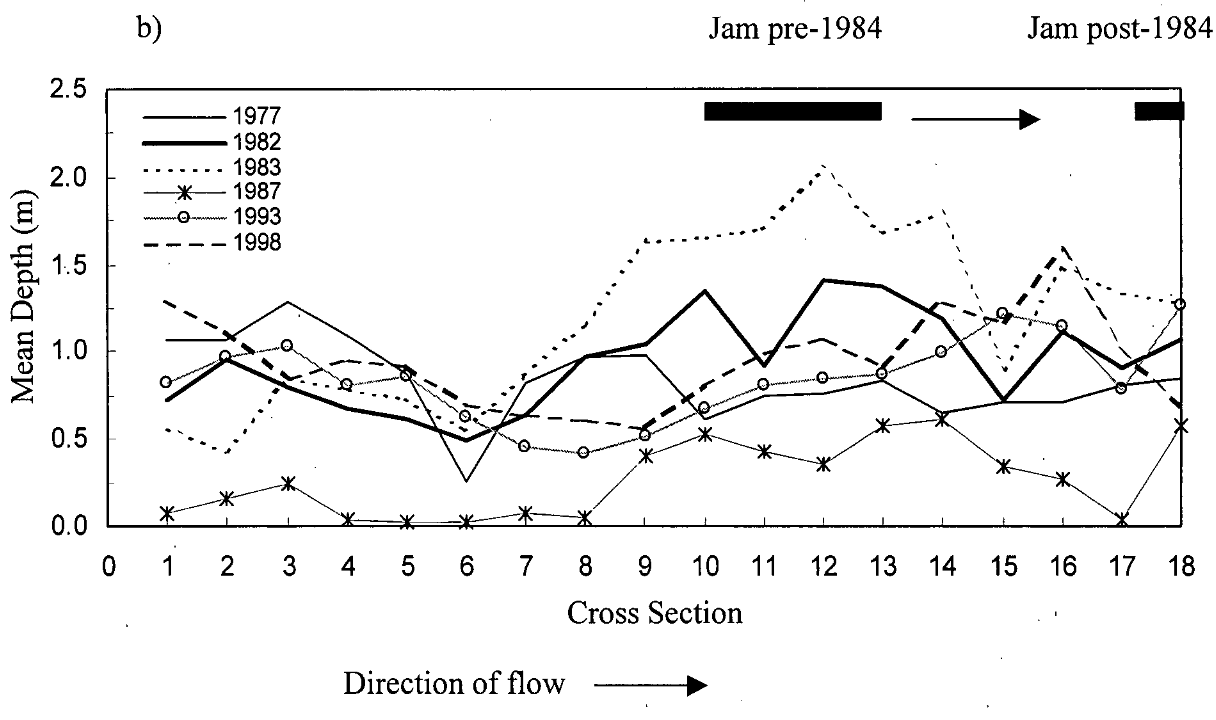
The effect of jam development on mean cross sectional depth is shown in Figure 12. Figure 12a shows the mean depths of the selected cross sections in SA VIII. Mean depth remained relatively stable for all of the cross sections from 1977 until 1981. Small pools forced by individual pieces of LWD are apparent in XS 12 in 1973 and in XS 9 in 1978, the small pools can be identified in the plot as sharp increases in mean depth (Figure 12a). By 1979 sediment accumulation upstream of the jam forced the development of a pool upstream of the wedge; this is reflected in the increases in mean depth shown by XS 6 (1982-1984). Local scouring upstream and downstream of the jam occurred as indicated by the increased mean depths in XS 9 and XS 12 (1980-1981); these cross sections are located within the same scour hole that eventually developed into a pool. Dramatic changes in mean depth are noted in 1984 when the channel is filled with sediment. The pool located in XS 9 and XS 12 was buried by over a meter of sediment following the events in 1984 (Figure 12a). The location of XS 18 within the jam is the reason for observed lag in mean depth decreases. In 1990, when the jam was breached, erosion of the upstream sediment wedge is evident by increased channel depth, which levelled

Figure 12. Average cross sectional depth in SA VIII for: a) selected cross sections, and b) selected survey years.

a)



b)

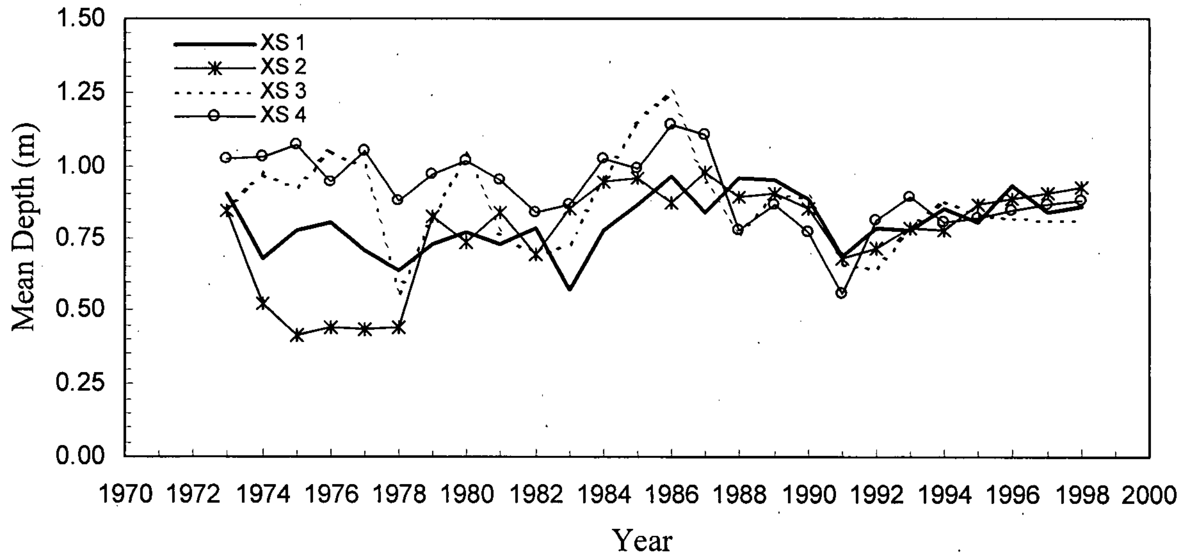


off to nearly pre-jam levels by 1991 (Figure 12a). The presence of the jam in XS 18 accounts for the minor perturbations witnessed in the cross section following 1990.

The graph of the mean annual cross sectional depths (Figure 12b) shows a similar developmental pattern as the plots for the selected cross sections. In 1977 ($\bar{x}$ = 0.84 m, σ = 0.23) mean depth was fairly homogeneous throughout the reach, with a slight decreasing trend upstream. In 1982 ($\bar{x}$ = 0.94 m, σ = 0.27) and 1983 ($\bar{x}$ = 1.19 m, σ = 0.50), the development of the previously mentioned pool is clearly seen in the graph and resulted in an overall increase in mean depth (Figure 12). The trend evident in the standard deviations of mean depth indicates that there is increased variability as pool morphology dominates the study area (σ = 0.23 in 1977 and σ = 0.27 in 1983). After the 1984 events and the arrival of the sediment wedge, the channel is almost entirely filled with sediment by 1987 ($\bar{x}$ = 0.27 m, σ = 0.22). This sedimentation causes a complete in-filling of pools and riffles upstream of the jam, resulting in low depth variability and a decrease in the mean depth of 64 % when compared to 1977 levels. By 1998 ($\bar{x}$ = 0.95 m, σ = 0.27) the channel had eroded the wedge sufficiently to restore mean depths to pre-jam levels. However, the presence of the wedge along the channel margin still constricts channel flow enough to create a fairly uniform channel, which is indicated by the low value in the standard deviation (0.27).

The temporal variability (1973-1982) in mean depth for the four selected cross sections, located in the uppermost portion of SA VII is presented in Figure 13. These temporal trends in mean depth reflect the influences of in-stream removal of major LWD pieces during harvesting (1976) and the subsequent removal of in-stream logging debris and the remaining LWD after the 1979 winter flow season. A trend of increased mean depth is evident in all four cross sections

Figure 13. Average cross sectional depth for the four selected cross sections in SA VII.

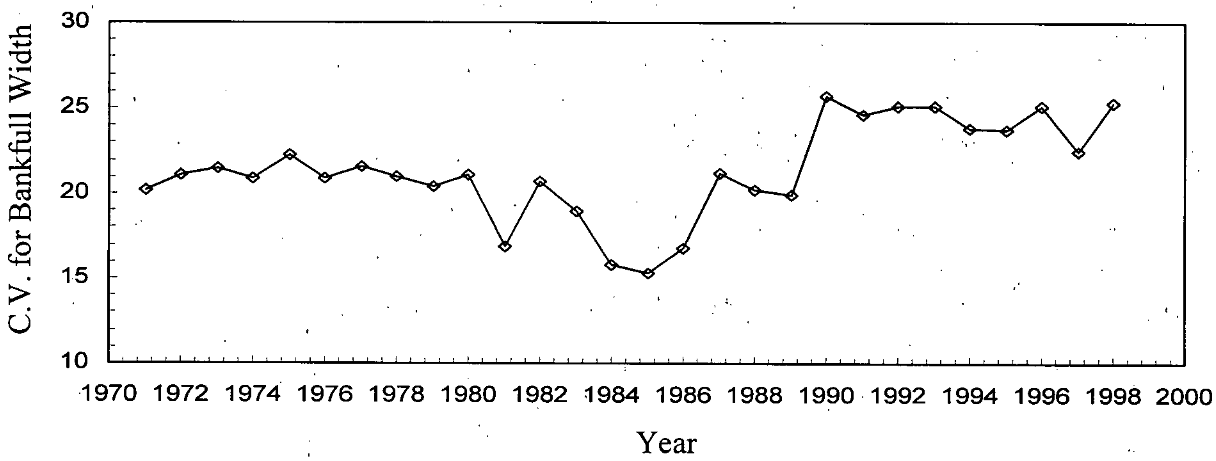


from 1982-1986 (Figure 13). This trend may suggest increased bed scour due to a reduced sediment load as a result of the development of the jam in SA VIII. Even after below average peak flows in 1985, increased scour is evident in 1985, suggesting that a decrease in the sediment supply may be responsible for the bed scour, not the peak flows.

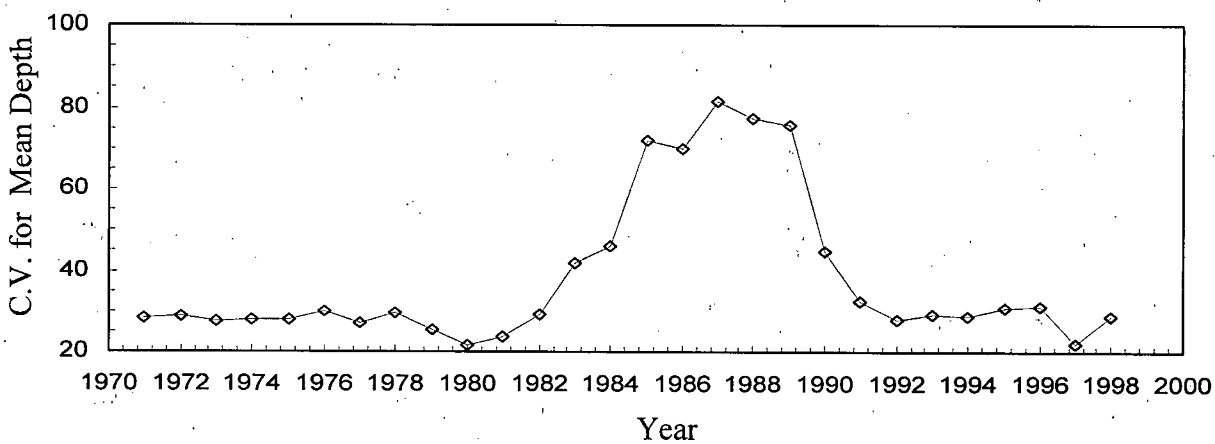
Figure 14 shows the plots of the coefficient of variation (CV) for the annual cross sectional values of bankfull width, mean thalweg depth, and the width to depth ratio. Bankfull widths exhibit increased variability from the pre-jam levels (Figure 14a). The channel remains relatively homogenous with the relict sediment wedge still dominating channel morphology along the right bank. Variability in the mean depths is relatively greater in comparison to that seen for bankfull widths. (Figure 14b). The fluctuations seen in the plot have been previously discussed. Channel depth does appear to recover much faster to channel disturbance associated with the 1984 events compared to bankfull width. Bankfull width has not yet recovered from the changes induced by the jam, and apparently will take much longer to recover to pre-jam levels than mean depth (Figure 14a & b). Width to depth ratios are frequently used to assess channel habitat and are therefore an important temporal metric (Figure 14c). Changes in the width-depth ratio follow the development of the jam closely. Maximum values are reached in the years during which the jam is fully developed and is actively regulating sediment transport. Recovery of the width-depth ratio is only seen once the jam has been breached and sediment is once again regulated by channel flows (Figure 14c). The annual width-depth ratio for each of the four selected SA VII cross sections is presented in Figure 15. High variability in the ratio from 1973-1982 reflects the previously discussed high variations in mean depth during the same period (Figure 13). The period of jam influence (1982-1986) appears as a low trough on the plot for all years, and is to be expected given the results presented for bankfull widths and mean depths

Figure 14. Annual coefficient of variation (CV) for SA VIII of: a) bankfull width, b) mean depth, and c) width-depth (w/d) ratio.

a)



b)



c)

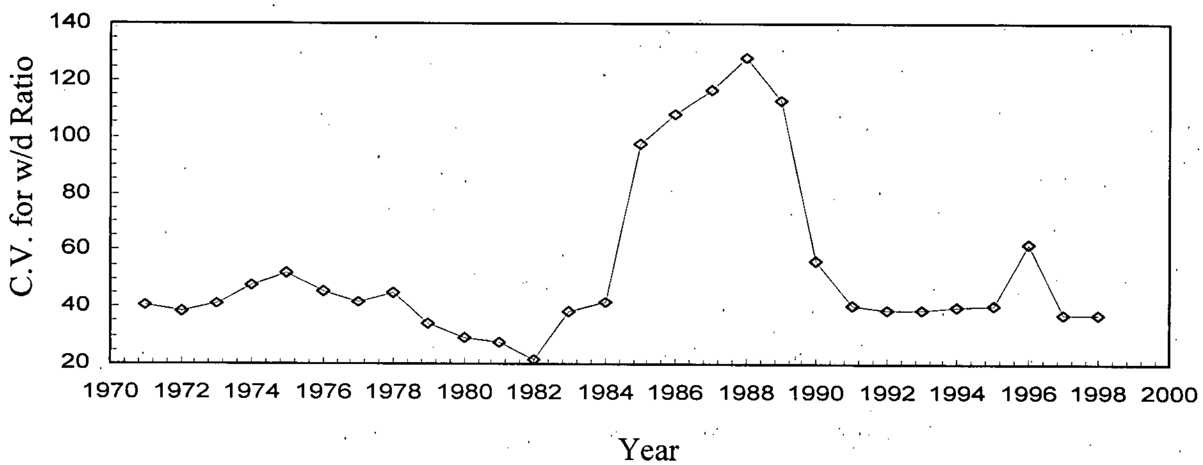
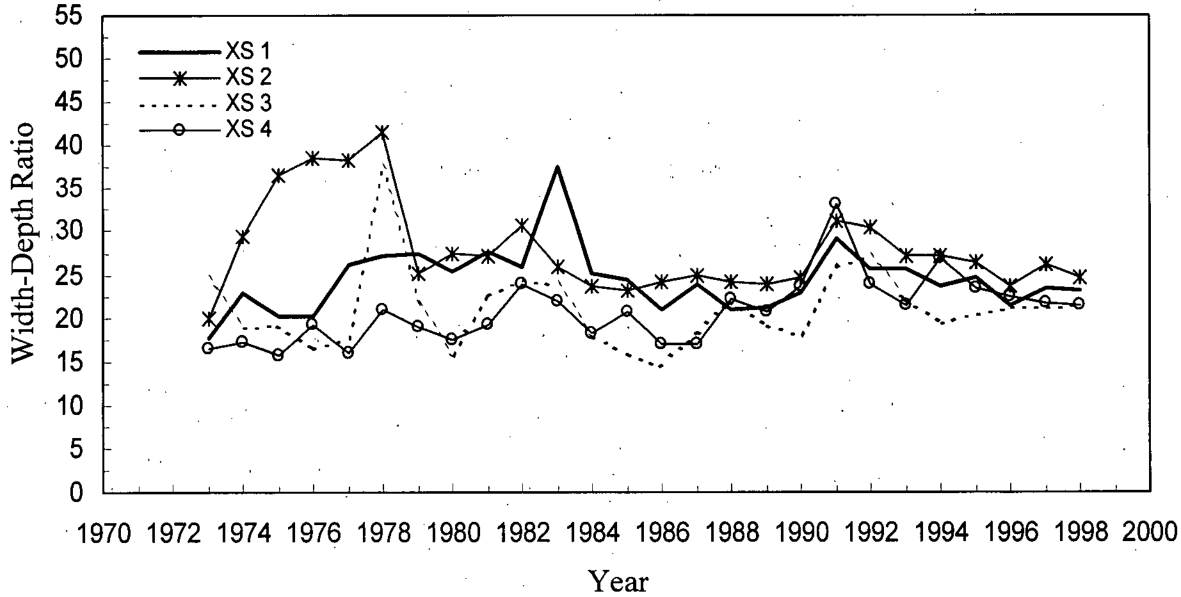


Figure 15. The annual width-depth ratio for each of the four selected SA VII cross sections.



(Figure 15). Although width-depth ratio may not be a good indicator for habitat variability, it appears to be a good rudimentary indicator of channel disturbance.

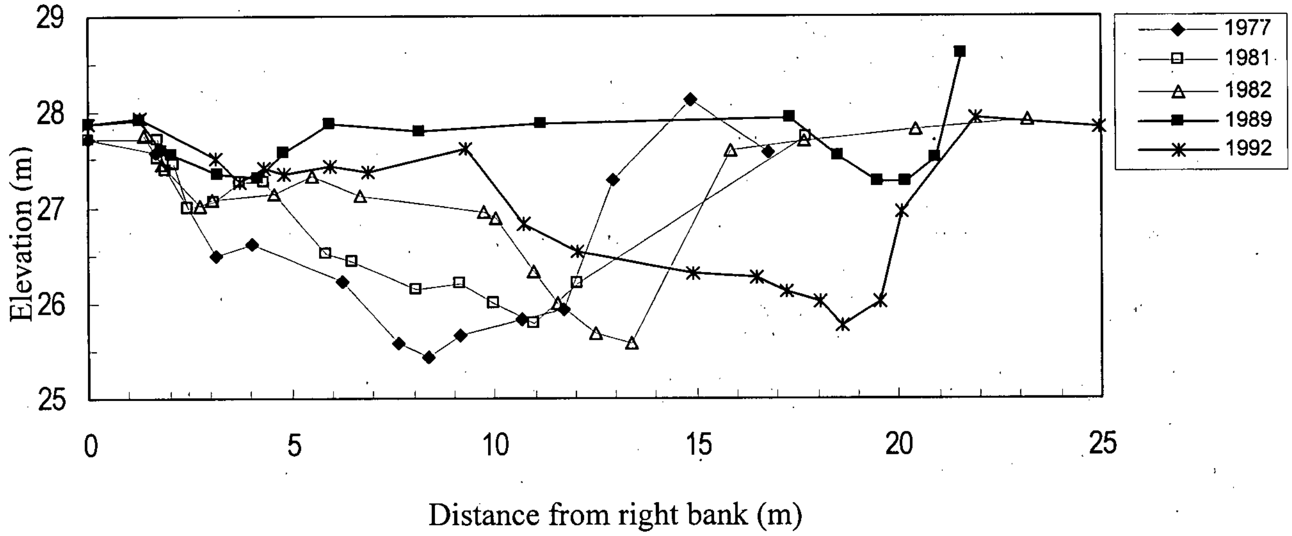
Plots of the SA VIII cross sections for years selected to represent the greatest change are presented in Figure 16. Relatively little change occurred in the shape of XS 3, the furthest upstream cross section (discussed in this section) before the arrival of the advancing bar (discussed in the previous section) in 1981 (Figure 16a). By 1982, the bar had nearly filled the entire pre-bar cross section and directed channel scour into the left bank. The development of the jam and the 1984 debris flow lead to a gradual in-filling of XS 3 until its maximum aggradation in 1989 (Figure 16a). The 1990 storm resulted in the rapid excavation of XS 3 and from 1992-1998 the cross section retained the same shape, which is fairly similar to its pre-jam shape. The combination of the advancing bar and the development of the upstream jam-related wedge has led to the leftward migration of this cross section by about 9 m in 10 years (Figure 16a).

XS 6 is nearer to the jam, especially during 1981 and 1983, than XS 3. Change in the cross sectional profile of XS 6 is evident in 1980, the first appearance of jam-related sediment deposition. The downstream advancement of the migrating side bar and the upstream advancement of the jam-related wedge caused a restriction of the cross sectional area in XS 6 by 1983 (Figure 16b). After 1984 sediment accumulated in the cross section and by 1987 the maximum height of the wedge exceeded channel bank elevations by 0.5 m, on average. The increased transport and mobility of sediment following the 1990 season resulted in the excavation of the wedge and formation of a more stable cross section (see 1992 in Figure 16b). Similar to XS 3, XS 12 moved 10 m to the left after a ten year period.

Figure 16. Selected annual cross sections of SA VIII to show years of greatest change for: a) XS 3, b) XS 6, c) XS 9, d) XS 12, and e) XS 18.

a) Cross Section 3: i) 1977,1981,1982, 1989, and 1992; ii) maximum changes.

i)



ii)

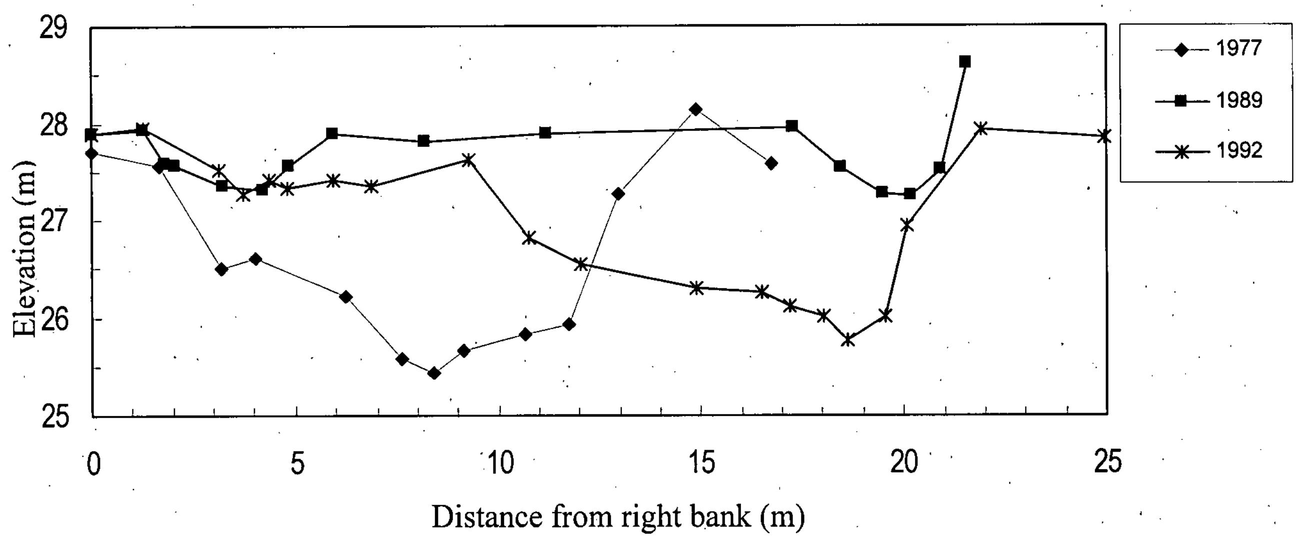
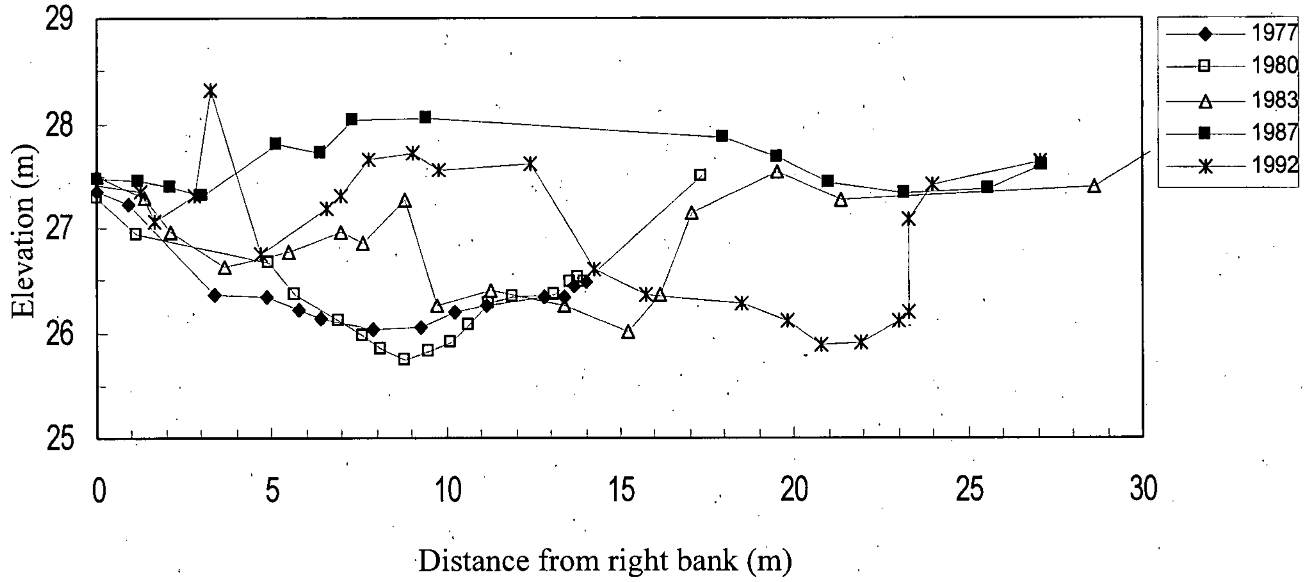


Figure 16. continued

b) Cross Section 6: i) 1977,1980,1983, 1987, 1992, and ii) maximum changes

i)



ii)

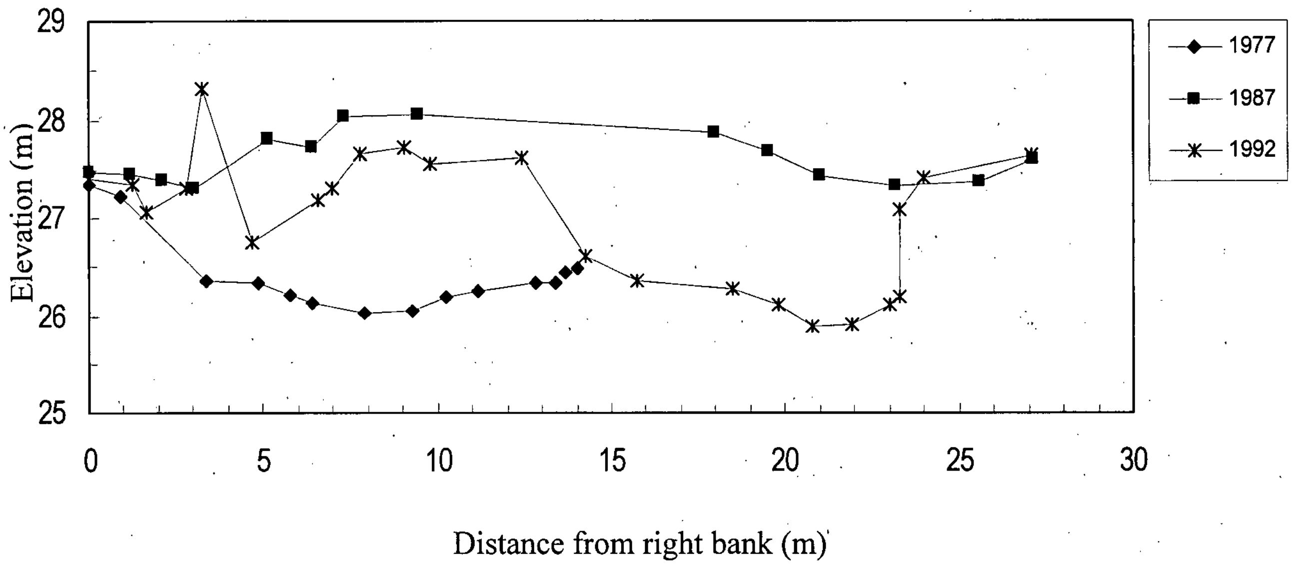
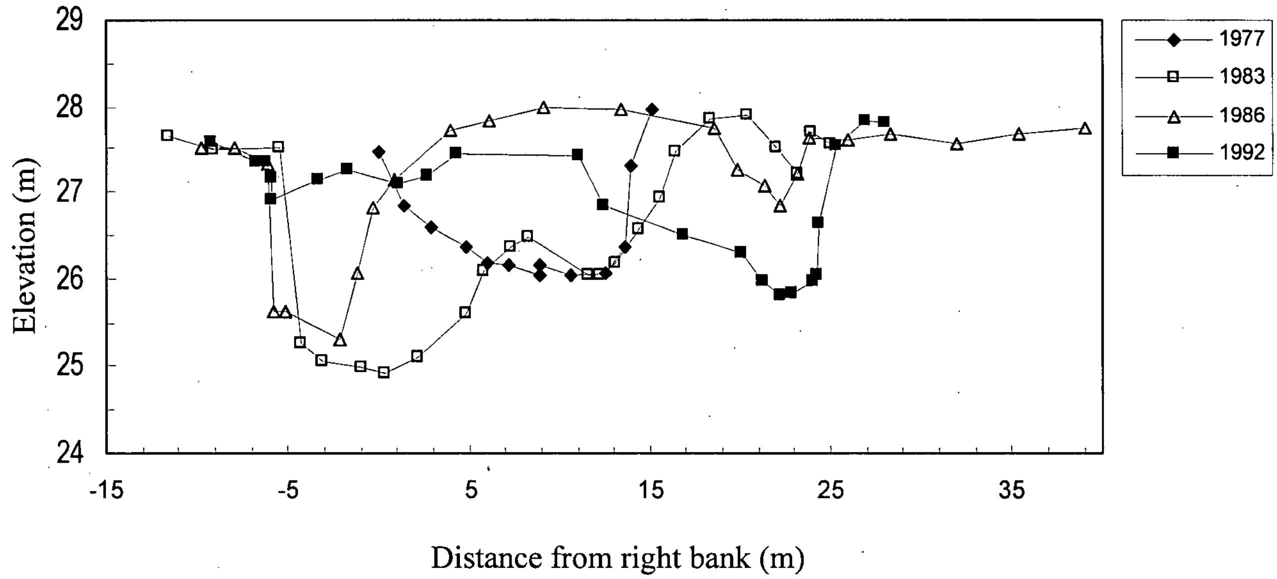


Figure 16. continued

c) Cross Section 9: i) 1977, 1983, 1986, and 1992; ii) maximum changes

i)



ii)

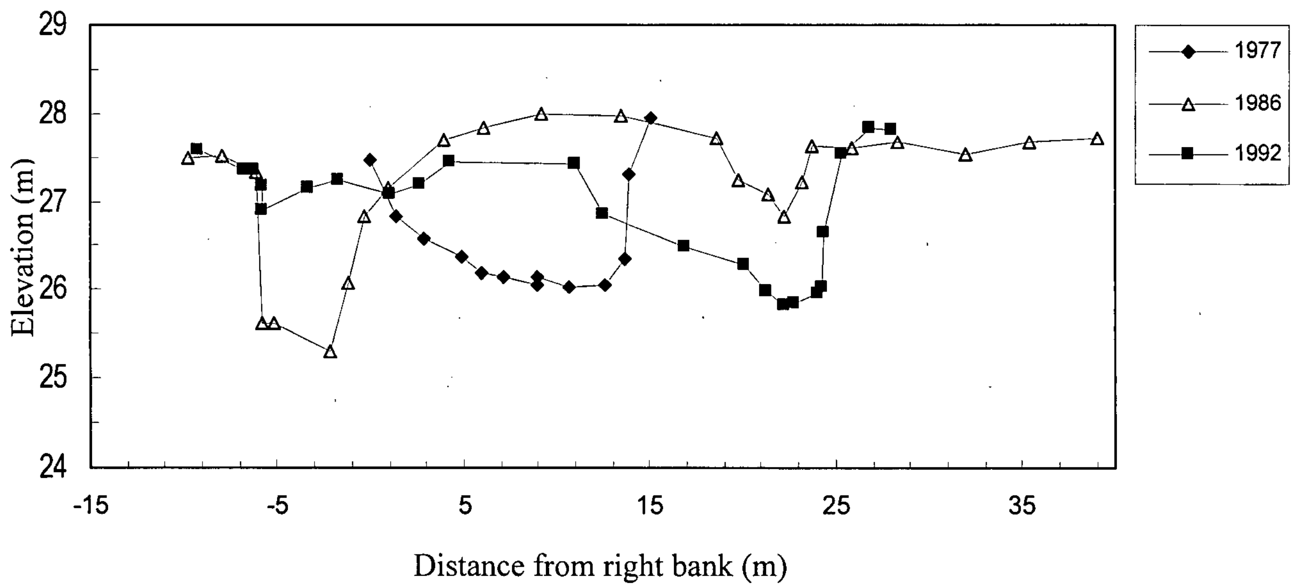
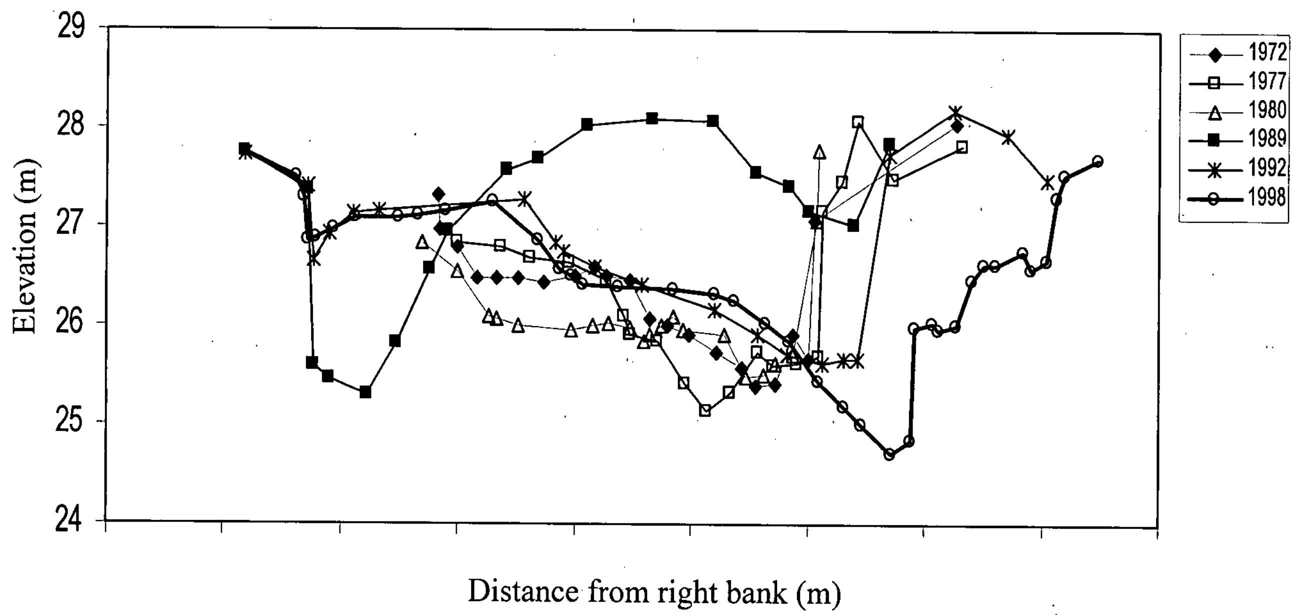


Figure 16. continued

d) Cross Section 12: i) 1972, 1977, 1980, 1989, 1992, 1998; ii) maximum changes

i)



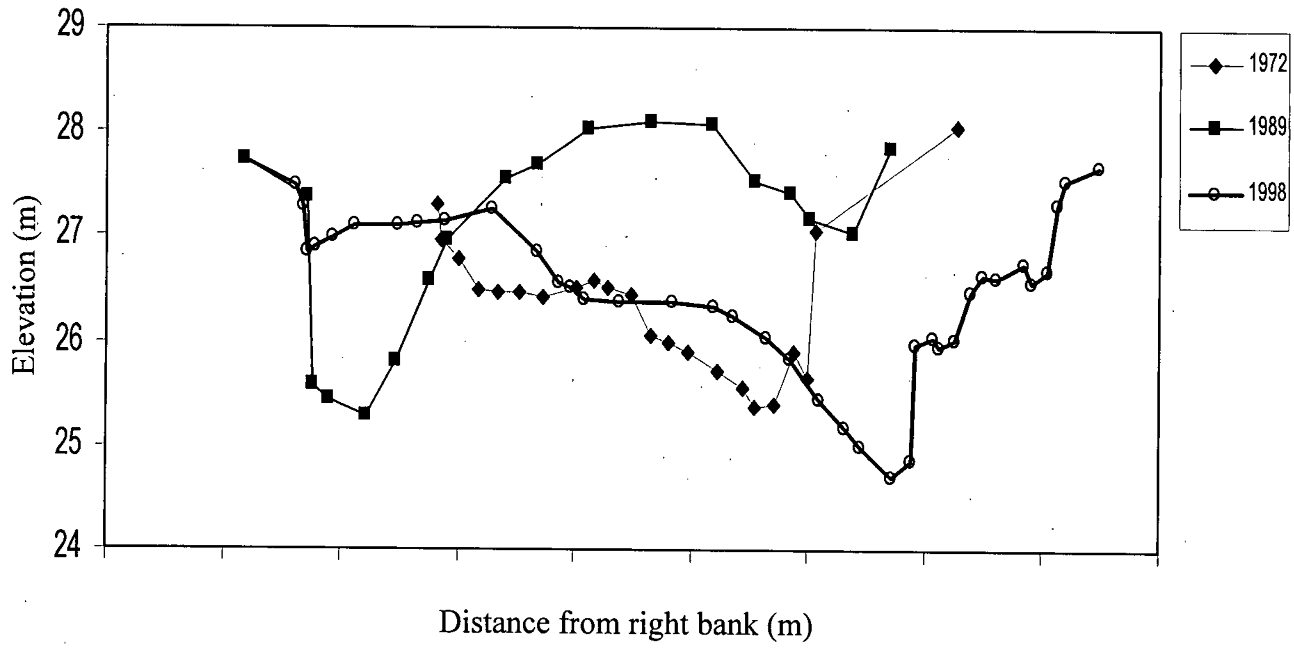
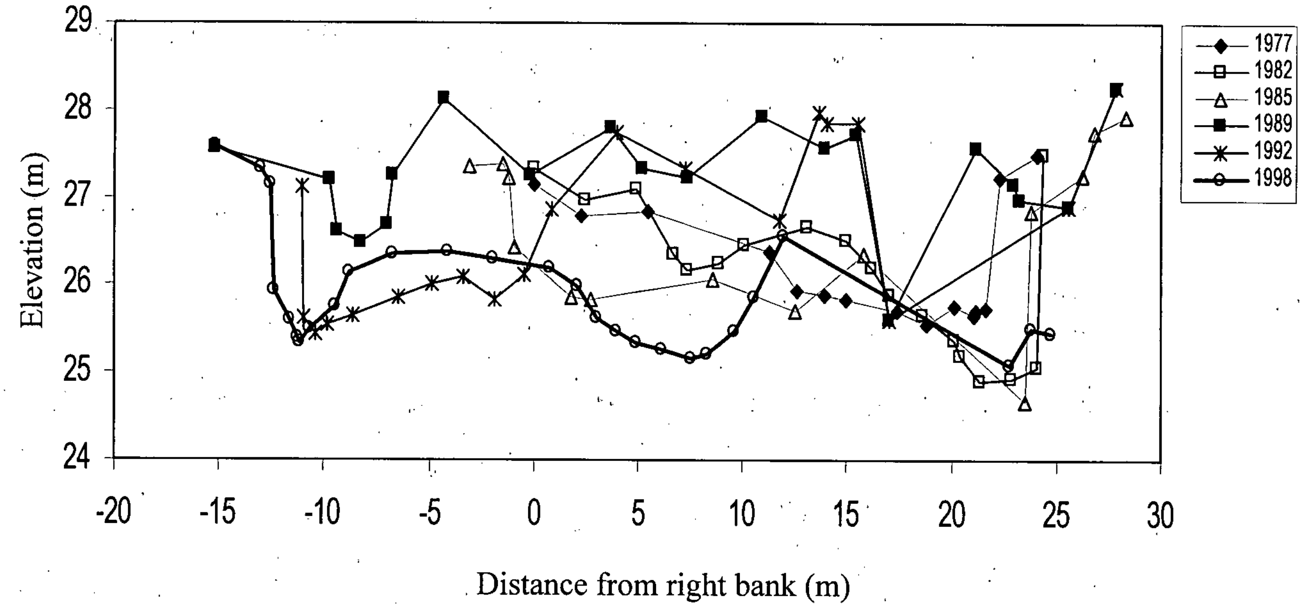


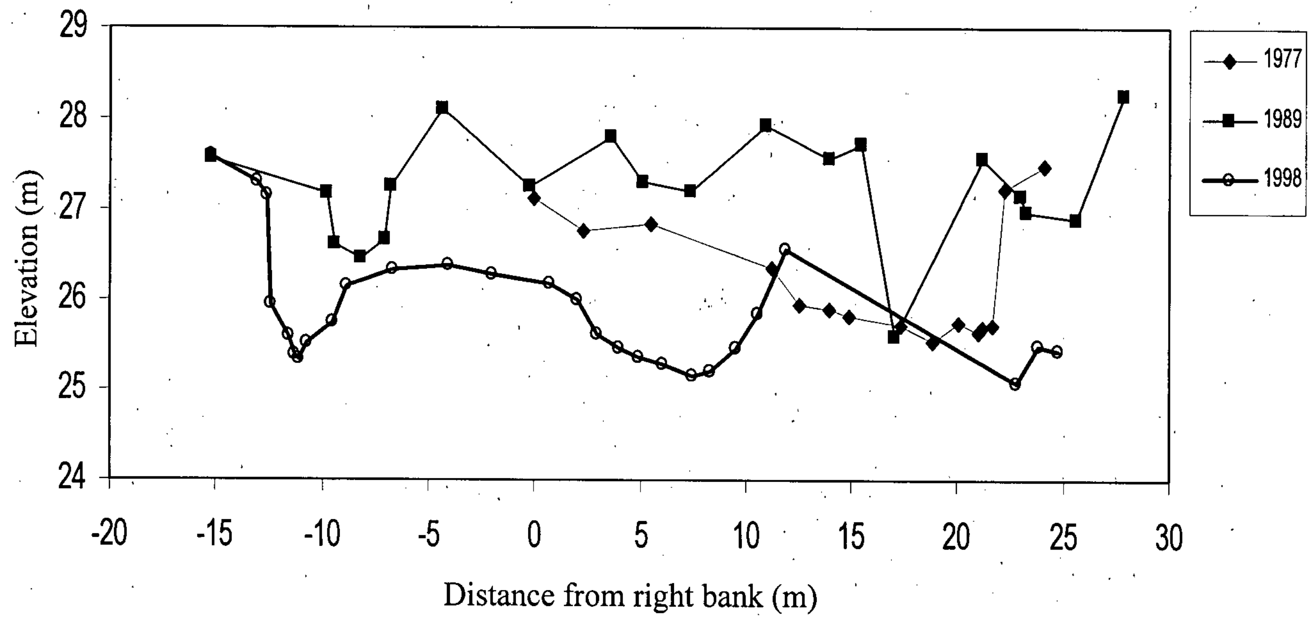
Figure 16. continued

e) Cross Section 18: i) 1977, 1974, 1980, 1989, 1992, 1998; ii) maximum changes

i)



ii)



The pre-jam cross sectional profile of XS 9 remained relatively stable from 1972 to1980 (Figure 16c). The development of the deep scour pool on the right bank can be clearly seen in the 1983 plot. The development of the wedge upstream of the jam resulted in the fill that is evident along the left bank and forced the position of the scour hole further along the right bank (Figure 16c). As with XS 6, the height of the accumulating wedge exceeded the height of both banks by 1986, and likely resulted in frequent overbank flooding during peak flows at this cross section (Figure 16c). The deep pool was buried following the 1990 event when the channel attained its current form (Figure 16c).

The presence of the key log in XS 12 led to earlier instability in its cross sectional form compared to other cross sections. Minor perturbations in the cross sectional form of XS 12 occurred between 1974 and 1980 (Figure 16d). The presence of the jam led to the development of a pool that has already been discussed; the pool attained its maximum cross sectional shape in 1983 (Figure 16d). The deposition and subsequent growth of the sediment wedge led to similar changes in the cross sectional shape of XS 12 as it did with XS 6 (see 1989 and 1992 Figure 16d). The last major change in the shape of XS 12 occurred following a 1995 storm during which the left bank partially collapse (Figure 16d).

Changes in the cross sectional form of XS 18 are very complicated in comparison to the other cross sections that have been discussed (Figure 16e). Relatively little change occurred in the shape of XS 18 from 1971 to 1980; during this period the right side of the cross section was occupied by a wedge related to the jam downstream of SA VIII (Figure 16e). Growth of the wedge in 1982 induced scouring along the left bank resulting in an increased thalweg depth. With the movement of the jam into XS 18, its shape changed dramatically (Figure 16e). The thalweg depth along the left bank was further increased in 1985 and development of a secondary channel is evident along the right bank (Figure 16e). Sediment accumulated in the channel until 1989, when mid-channel heights exceeded local bank elevations. The 1990 storm season resulted in substantial scouring of the sediment that occupied the cross sectional area of XS 18. The remainder of the wedge was removed in 1991 and the channel retained its shape until 1998. In contrast to the other cross sections that migrated from the right to the left bank, XS 18 migrated from the left to the right bank. No significant trends were evident in the cross sectional plots of SA VII and therefore they will not be discussed in detail.

Changes in both thalweg elevation and channel sinuosity are evident in the longitudinal plots in the selected years at SA VIII (Figure 17). Increased distance along the thalweg reflects increased sinuosity in the channel. Channel sinuosity for SA VIII was calculated as thalweg length divided by straight-line channel length (45 m). The maximum thalweg length of 151.5 m was attained during the 'jam maturity' phase in 1988 (Figure 17). This translated into a maximum channel sinuosity during the period of observation of 3.37. This is considerably greater than pre-jam values for thalweg length and channel sinuosity of 67.9 m and 1.51 respectively. Increased sinuosity reflects the braided nature of the channel upstream of the 'mature' jam, when more than one channel will likely be located on top of the wedge. Subsequent scour of the wedge is reflected in decreased thalweg lengths, although by 1998 the thalweg length is still 15 m greater than pre-jam (1977) levels.

Temporal variations in areal scour and fill are shown for selected cross sections of SA VIII (Figure 18). Prior to 1979, scour and fill in SA VIII were relatively minor. The onset of logging and the occurrence of a relatively large flow event in the fall of 1978 resulted in larger scour and fill values in 1979 than previously observed. Development of the jam resulted in increased channel scour and fill. The largest increases in scour and fill are seen in areas that

Figure 17. Longitudinal profile plots for selected years of SA VIII.

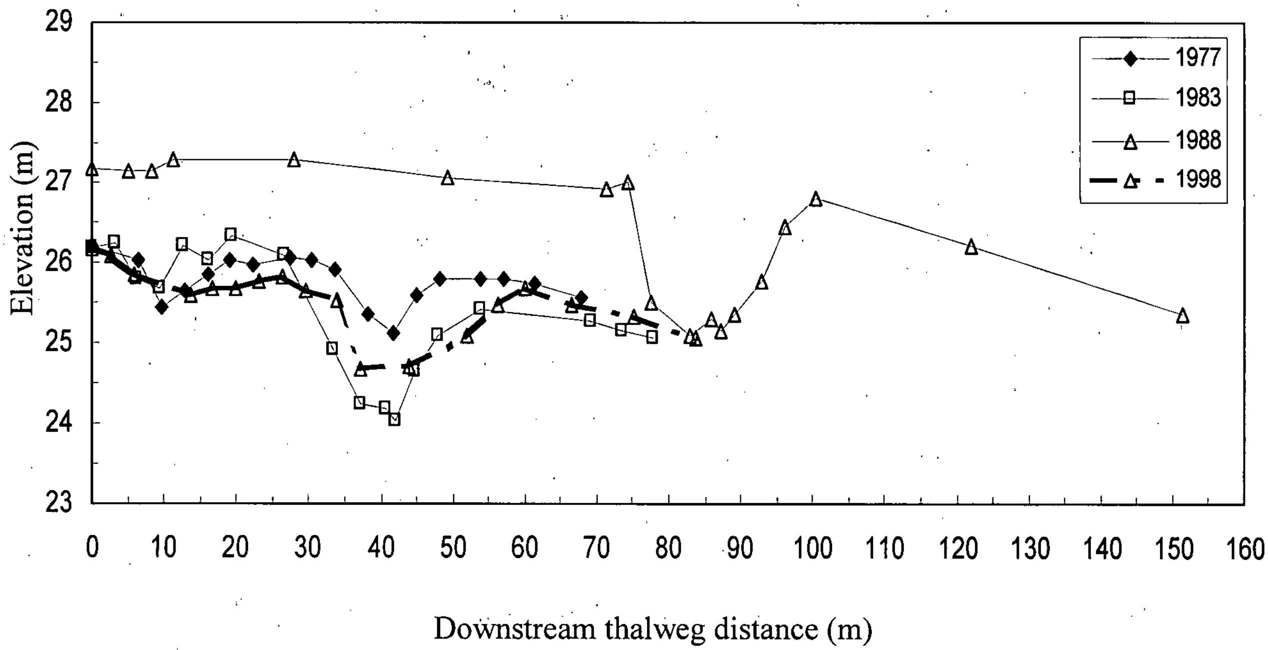
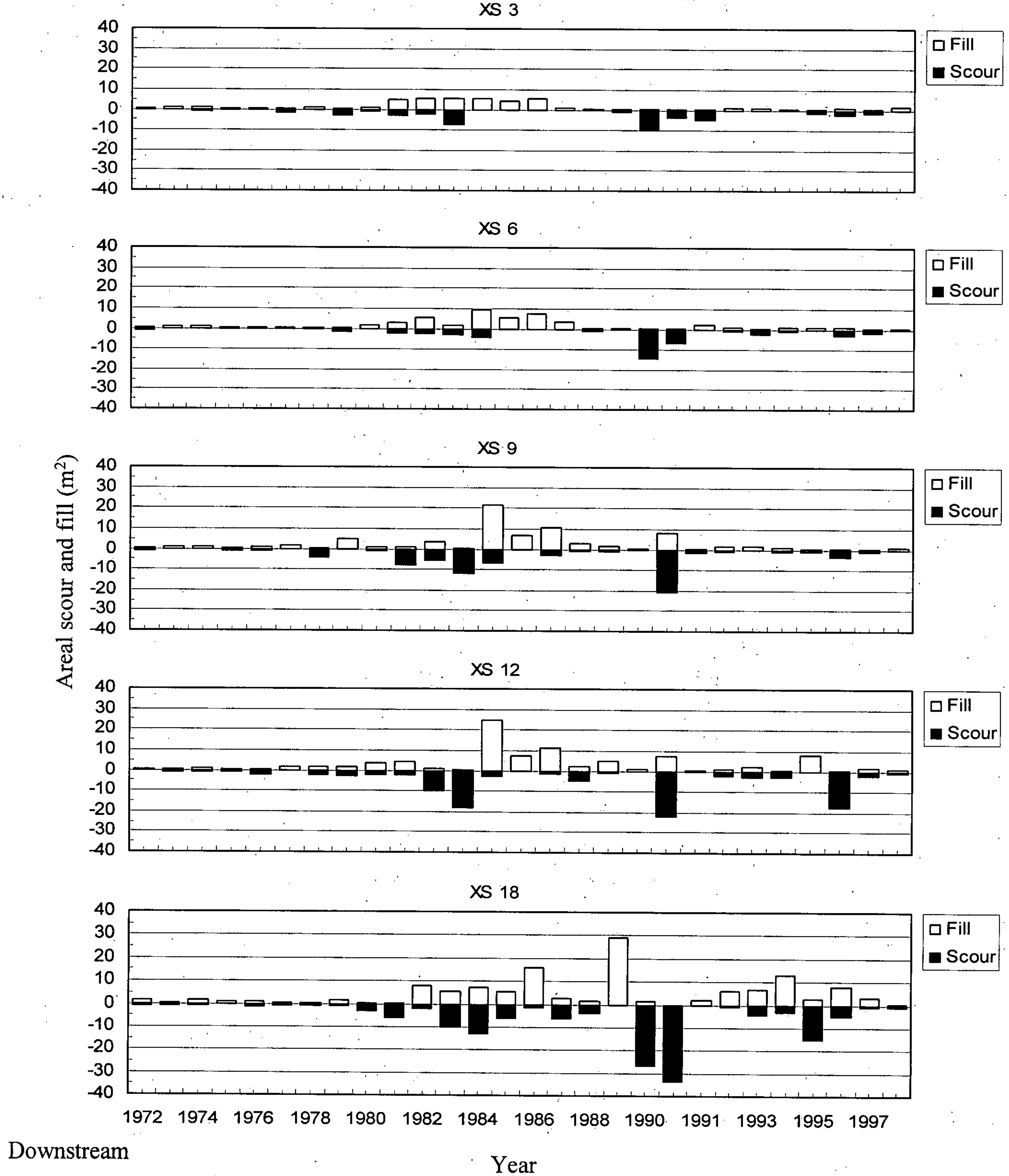


Figure 18. Annual scour and fill (m^2) for SA VIII: XS3, XS 6, XS 9, XS 12, and XS 18.



were directly influenced by the presence of the jam (i.e., XS9, XS12, and XS18). Most of the scour and fill that occurred in these areas were associated with structural changes in the jam. The largest amounts of channel scour and fill occurred during the period of 1982-1990. The effect of the 1990 storm season is clearly reflected by changes in the channel cross sections, which exhibited their highest recorded values of scour for the entire study period (Figure 18). The 1995 peak flow event further degraded the sediment wedge as indicated by the scour amounts for XS 12 and XS 18 (Figure 18). The greater variation exhibited by the scour and fill of XS 18 following 1990 is believed to result from movements of individual pieces of LWD within the jam. Figure 19 shows the general trends in scour and fill just discussed.

Since SA VII is located downstream of the jam it is expected to scour when sediment is trapped upstream by the jam and fill when the wedge is eroded. The relative amounts of areal scour and fill are much less for the four selected cross sections of SA VII than for those in SA VIII (Figure 20). The effects of the jam on the scour and fill processes in SA VII are therefore hard to isolate. It is, however, interesting to note the apparent wave like pattern evident in the scour and fill plots. This wave like pattern appears to crest during logging (1978-1979), with the amplitude becoming progressively muted with time after logging. It is possible that waves of sediment are responsible for the pattern (Figure 20). Such patterns would be consistent with concepts of bedload transport (Knighton, 1998). Close examination of the plots for SA VIII (Figure 18) and SA VII (Figure 20) reveal a potentially similar wavelike pattern. The presence of the jam in SA VIII seems to amplify this pattern, although the wave amplification does not translate downstream to SA VII. However, the scour of the wedge (Figure 18) following the 1990 event does translate downstream and is seen by increased fill in all of the SA VII cross sections (Figure 20). In forested streams, therefore, jams are an additional mechanism

Figure 19. Annual scour and fill (m^2) for SA VIII from 1971-1998.

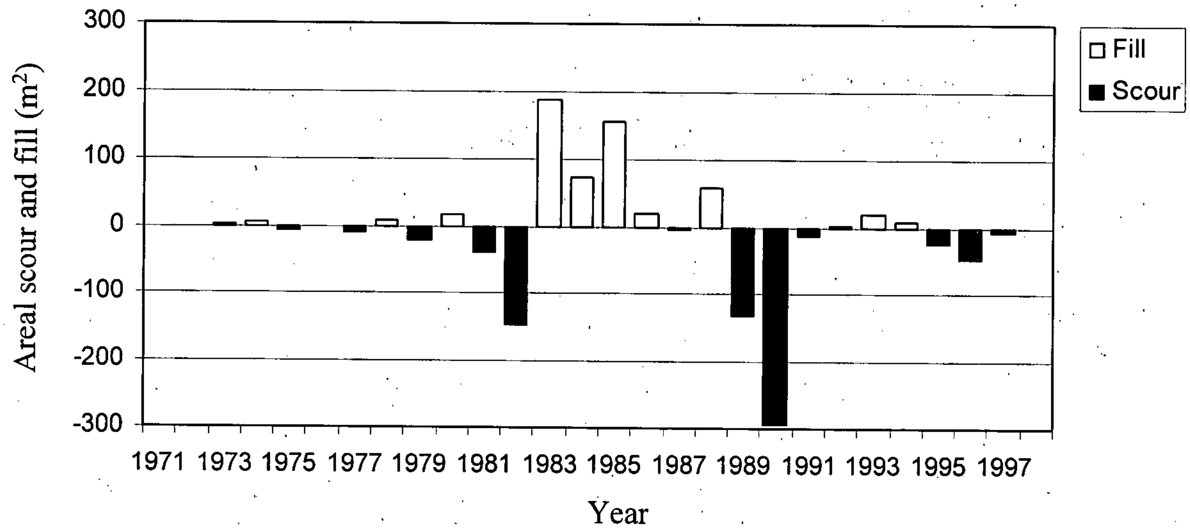
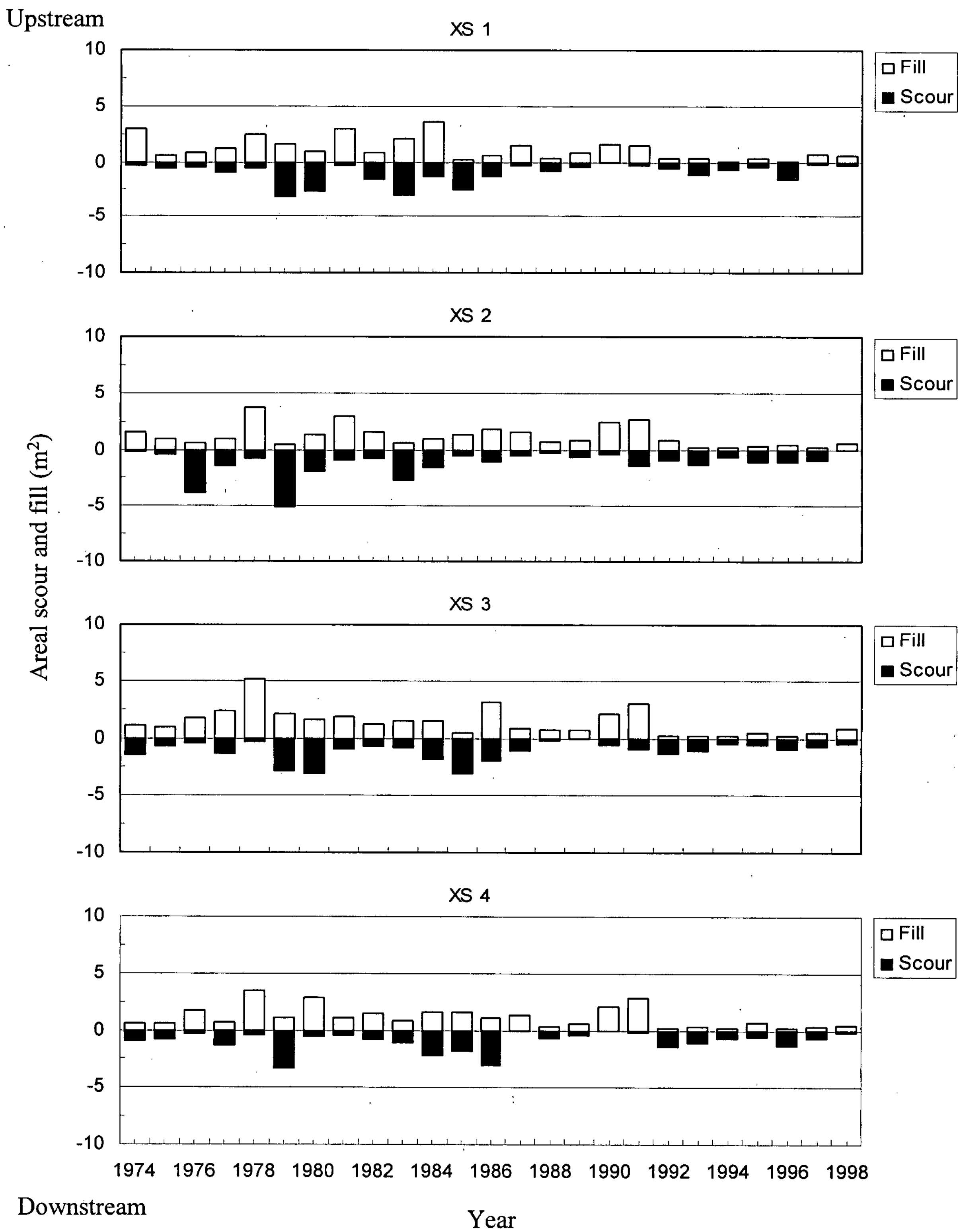


Figure 20. Annual scour and fill (m²) for SA VII: XS1, XS 2, XS 3, and XS 4.



responsible for generating temporal variations in bedload transport rates to those identified by Gomez *et al.* (1989).

Summary of Cross Sectional Analysis

The annual cross sectional surveys allowed a detailed examination of the morphologic changes induced by the development of a channel spanning jam. Even though the jam developed in 1977 and grew dramatically following logging, it was not until after a 'conditioning' flow occurred and compressed the jam matrix (making it more impermeable to sediment transport) that the jam began to alter channel morphology. Changes observed upstream of the jam included: increased channel widths; decreased channel depths; increased potential for overbank flooding; and channel migration. The development of channel cross sectional form near or within jams is very complex, with scour and fill occurring simultaneously. It is hypothesised that the cross sectional form is mostly dependent upon the complex flow patterns that develop in the vicinity of a jam and are controlled by the individual pieces that comprise a jam. For the most part, except XS 18, the cross sectional shapes have returned to their pre-jam forms. The effect of the jam on SA VII is not as definitive, but observed fluctuations in mean depths are indicative of changes brought about by a reduction in sediment transport.

The results of the cross sectional analysis show that the channel can respond dramatically to structural and temporal changes in the jam. In essence, the channel co-evolves with the jam. Minor perturbations in channel cross sectional form were associated with the 'jam adolescence phase'. During this phase the jam was a loose assemblage of individual pieces of LWD which had accumulated around a key member piece. After a 'conditioning' storm event the jam evolved into the 'jam maturity phase'. During this phase dramatic changes in cross sectional form occurred as the sediment wedge dominated the channel. Once the jam was breached after the 1990 storm season, the 'jam senescence phase' began. The primary characteristic of this phase, in terms of channel morphology, is the erosion of the upstream wedge and the re-establishment of cross sectional form. These findings confirm that jams can exert a primary control on channel morphology. Additionally, the spatial and temporal affects of the jam on channel morphology was linked to the life stage of the LWD structure.

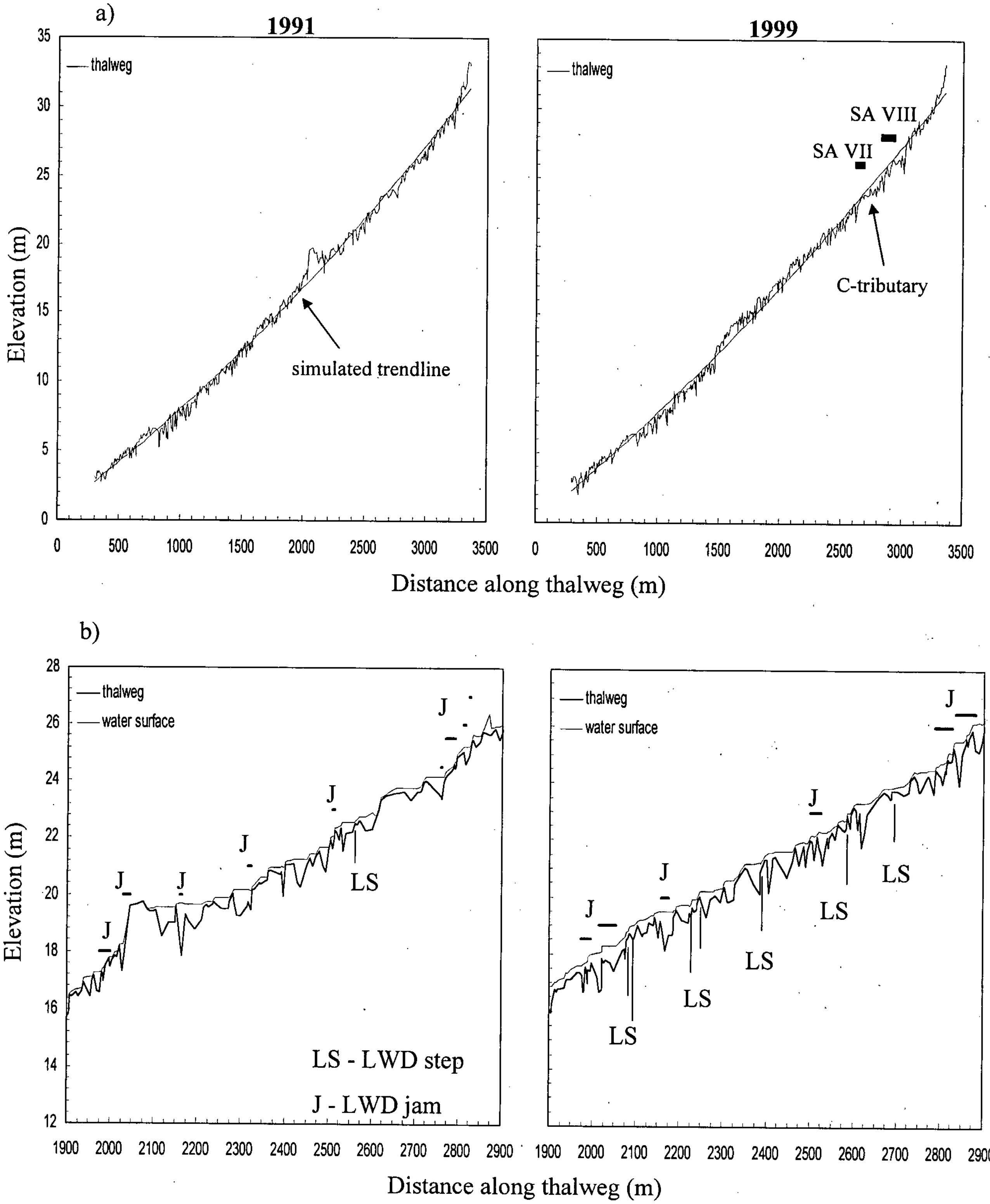
Longitudinal Profiles

Introduction

The previous section established that an individual jam has significant impacts on channel morphologic parameters and that these impacts are temporally variable. However, jams are not isolated occurrences along the longitudinal profile of a stream. In this section the spatial importance of jams on the longitudinal profile of Carnation Creek will be explored in terms of both their spatial and temporal dynamics.

Previous research has indicated the importance of LWD on the longitudinal profile of a stream. Robison and Beschta (1990) characterised the longitudinal profiles of selected streams in Alaska with high woody debris loading as 'choppy' and 'highly variable'. Small scale variabilities in a longitudinal profile can be attributed to morphologic units, such as pools and riffles (Hogan, 1986). The frequency of these units has already been shown to increase in forested streams and this should, therefore, translate into increased variability of the longitudinal profile. Additionally, jams have been found to be responsible for large scale variabilities (or convexities) in the some longitudinal profiles (Mosley, 1981).

Figure 21. Longitudinal profiles for Carnation Creek (1991 and 1999): a) entire longitudinal profile for both years (a second-order polynomial trendline added to make visual inspection easier); b) detailed longitudinal profiles of a selected section for each survey year.



The longitudinal profiles of Carnation Creek for 1991 and 1999 are shown in Figure 21. In order to make visual inspection of the longitudinal profiles easier a second-order polynomial was fitted using least squares to the thalweg profile (Figure 21a). The 'choppy' and 'highly variable' nature of longitudinal profiles of forested stream are clearly evident in both survey plots.

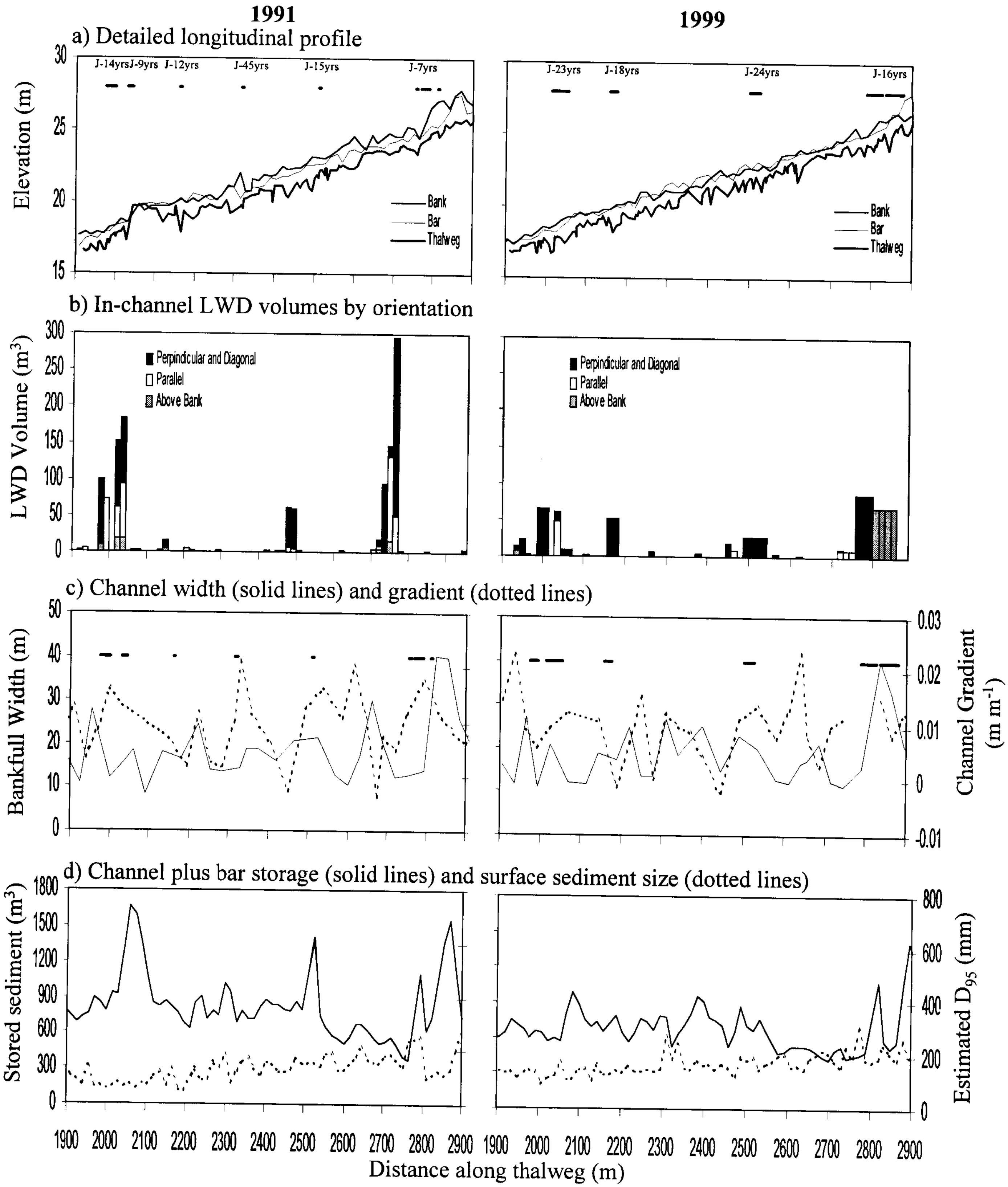
Detailed profiles of a selected section from the 1991 and 1999 surveys clearly illustrate the importance of LWD jams on the longitudinal profile. This evidence is seen by large scale variabilities or convexities in the thalweg elevation, most notably, upstream of jams (Figure 21b). These 'convexities' are the result of extensive sediment accumulation upstream of LWD jams. Major sediment wedges are formed upstream of large channel spanning jams or multiples of jams that are closely spaced.

Longitudinal Profile Surveys

Detailed longitudinal profiles, which include thalweg profiles, bar and bank top elevations, are presented along with the relative location and age of jams (Figure 22a). Areas where bar and bank top elevation merge indicate areas where sediment accumulation has reached the channel's storage capacity, thus are probable sites of overbank flows. Convergent bar and bank zones frequently occur at sites upstream of channel spanning jams and have been found to be a critical prerequisite for the development of off-channel habitat at Carnation Creek (Eaton, 1994). The convergence of bar and bank zones was clearly presented during the analysis of SA VIII.

The influence of jams on channel morphology will change with time as a jam's structure is altered by flows and individual pieces within the jam rot and decay. The contrast of sediment accumulation upstream and scour downstream of a jam is more pronounced around 'younger'

Figure 22. a) Detailed longitudinal profile of a selected section of the 1991 and 1999 survey, showing thalweg, bar and bank elevations, as well as jam age and location. b) LWD volumes by orientation. c) Channel width (m) and channel gradient (m m^{-1}). d) Channel plus bar stored sediment (m^3) and surface sediment size, estimated D_{95} (mm).



jams. This contrast between upstream and downstream locations dissipates with time as the trapping efficiency of jams decline (Figure 22a).

A large sediment wedge at 2050 m in the 1991 survey is noticeably absent by the 1999 survey. This wedge accumulated behind a channel spanning jam. The riparian area surrounding the channel in the vicinity of the jam was logged according to the 'intensive treatment' during 1976 and 1977. Through a series of morphological maps and low elevation photographs, the temporal sequence of jam development and subsequent morphological perturbation was assembled, similar to the procedure used for SA VIII. The foundation of the jam was an individual key member LWD piece that spanned the entire main channel. The key member first appeared in a 1977 morphological map (not included); many small cut pieces of LWD, as a result of intensive riparian logging, had already accumulated around this piece because of the short time of its existence. Evidence of logging slash strewn throughout the channel was seen in the 1977 photograph. Sediment upstream of the jam was alternatively deposited and scoured until 1987, thus the period from 1977 to 1987 would constitute the jam's 'adolescence phase'. Then in 1987 extensive sedimentation upstream of the jam was evident. As a result of jam 'conditioning' following the 1986 peak flow season, the jam entered its 'maturity phase'. Additional pieces of LWD had been added to the matrix of the jam since the previous year, leading to its increased integrity. The increased integrity of the jam also coincided with the arrival of a migrating sediment bar that reached the upstream end of the jam in 1987. In subsequent years, sediment proceeded to fill the entire channel upstream of the jam as the jam interrupted downstream sediment transport as well as the downstream migration of the bar. As shown in the cross sectional analysis (Figure 12) the resultant reduction in channel depth upstream of the jam likely induced frequent overbank flows in the vicinity of the wedge.

Evidence of the development of various side channels was obtained from the low elevation photographs, and it is hypothesised that these channels transmitted water downstream during peak flow events. A bankfull event in 1995 eventually established one of these side channels as a more permanent course, leaving both the jam and sediment wedge isolated from the main channel.

This sequence of events illustrates the role of jams in floodplain evolution by: 1) forcing the lateral migration of the channel; 2) causing the frequent inundation of the floodplain during high flow events (not necessarily the historically bankfull events); 3) creating temporary storage sites for volumes of sediment in wedges that accumulate behind the jam; 4) creating longer term storage sites for sediment when the wedges are isolated from the main channel course (as was previously discussed) and 5) leading to the development of off-channel habitat by forcing secondary flow channels.

Figure 22b shows in-channel LWD volumes by orientation. The difference in the volume of LWD for most of the jams from 1991 to 1999 is due to increased thalweg length in the jam's vicinity. By observing the location of jams in Figure 22a it can be seen that large volumes of LWD are associated with jam locations (Figure 22b). In addition to being sites of high LWD volumes, jams appear to fix the orientation of wood pieces in either a perpendicular or diagonal direction to the channel for long periods of time. LWD that is oriented parallel to flow is less likely to alter channel morphology than are pieces which are either perpendicular or diagonal to flow (Beschta, 1983; Hogan, 1987). It was observed that in some instances individual jam pieces that were parallel in 1991 became reoriented to appear in either a perpendicular or diagonal direction in 1999. It is hypothesised that this may be an important mechanism for the re-entrainment of LWD and thus could exert greater control on channel morphology. The much larger volume of LWD above bank in 1999 compared to 1991 suggests the isolation of entire jams or parts of jams in 1999 as a result of channel migration (Figure 22b).

Channel width is dramatically influenced by the presence of LWD (Keller and Tally, 1979). Nakamura and Swanson (1993) found that the greatest channel widths commonly occurred upstream of jams. Additionally, increased bankfull widths were observed upstream of the jam in SA VIII, however, width was also dependent upon time. At Carnation Creek similar results were found; channel widths were generally wider upstream and within jams (Figure 22c). Table 4 shows the variation in bankfull widths between the 1991 and 1999 surveys. The largest bankfull widths are associated with jams, LWD, and clear reaches respectively. The variability of bankfull widths in Carnation Creek as well as other forested streams raises the question of whether bankfull width is an appropriate scaling metric. This metric may change dramatically, as was shown in SA VIII, and whether this change is truly bankfull width needs to be investigated.

The greatest differences in channel width are seen in areas associated with younger jams, for example, the contrast between downstream and upstream channel widths at the 7 year old jam in the 1991 survey (Figure 22c). As a jam ages and its ability to alter flow patterns decreases, the contrast between the downstream and upstream channel widths decreases (e.g., compare the 15 and 45 year old jams in the 1991 survey, Figure 22c). The temporal extent of a jam's influence on channel width, however, persists even after the jam is no longer present. The forty-five year old jam located in the 1991 survey was still associated with increased channel widths, even though the jam no longer significantly altered local channel morphology. In the 1999 survey the jam was no longer present, yet the channel remained relatively wide (Figure 22c).

Table 4. Mean bankfull width for the overall survey, reaches with neither LWD nor jams, reaches with LWD, and reaches with jams.

Mean Bankfull Width	1991	1999
	m	
Overall (S.D. [a])	17.07 (6.26)	17.75 (5.76)
Clear reaches	14.69	16.17
Reaches with LWD	15.77	18.91
Reaches with jams	20.07	22.45

[a] S.D. is standard deviation

Local channel gradient is also influenced by the presence of LWD jams (Figure 22c). Channel gradient increases in the downstream direction reaching a maximum immediately downstream of a jam. The increased channel gradient is due to downstream scour associated with the presence of a channel spanning jam. At greater distances downstream from the jam additional sediment is recruited from the banks and the effect of the jam on gradient decays. Gradient decreases immediately upstream of the jam due to the development of the sediment wedge. As jams age the upstream sediment wedge is eventually downcut and this sediment will be deposited downstream, resulting in the reduction of the gradient downstream of the jam.

Channel substrate is also dramatically affected by the presence of jams (Figure 22d) (Hogan, 1989; Smith *et al.*, 1993; Rice and Church, 1996; Sidle and Sharma, 1996). Upstream of jam locations a distinct trend of bed material fining that decreases with distance upstream of the jam is evident. Downstream of a jam bed material is generally coarser, but progressively fines with distance downstream of the jam. At 2800 m the effects of the 7 year old jams (1991) on sediment texture can be clearly seen, where a 300 mm difference between the estimated D_{95} upstream of the jams compared to downstream of the jams (Figure 22d). The contrast of the estimated D_{95} between the upstream and downstream locations of jams lessens overtime, as is evident in the 1999 plot.

Jams will also directly influence the amount of sediment stored in the channel (Figure 22d). Sediment volumes were found to be greatest at sites upstream of jams. However, the temporal and spatial extent of the sediment accumulation is strongly dependent upon the age of the jam. Variation in the volume of sediment stored storage in the 1991 survey is closely linked to its spatial proximity to jams (Figure 22d). The amount of stored sediment in the 1999 survey is noticeably lower, primarily due to the break down of jams in this survey section. Average bar volumes per bankfull interval were significantly different between the two surveys. In 1991, 145 m^3 of sediment was stored in bars per interval compared to 120 m^3 per interval in 1999.

The spatial extent of the influence of a jam on bed material, both upstream and downstream, is related to the structure and age of the jam. The type of jam structure is dependent upon the formational/depositional processes of the LWD that make up a jam (Braudrick et al., 1997). Jams that develop at the terminus of debris flows, are commonly tightly interlocked, thereby forming an effective sediment trap almost immediately. Generally, LWD introduced by landslides, earthflows, snow avalanches, and fluvial erosion form jams that are not tightly interlinked, and are therefore relatively permeable and allow water and sediment to continue downstream relatively unobstructed (Swanson *et al.*, 1976; Keller and Swanson, 1979; Hogan *et al.*, 1998). The jam aging sequence is, in part, dependent on which depositional process is responsible for the bulk of the LWD in a given jam. Hogan (1989) noted that jams formed by debris flows will commonly start the aging sequence almost immediately after deposition. Jams formed as a result of other processes, for example fluvial erosion, may or may not form a tightly interlinked jam after a 'conditioning' period.

The overall effect of jams on sediment storage was determined by calculating the volume of sediment stored in bars that were identified as being wedges in the field or through subsequent re-analysis of channel morphology through the use of the low level photographs. For the purposes of this analysis the entire length of channel surveyed during both 1991 and 1999 was considered. Twenty-one jams were identified as having associated upstream wedges in 1991. In total these wedges accounted for 10, 100 m^3 of sediment, approximately 47 % of the total sediment stored in bars (21, 400 m^3). In 1999, 20 jams were identified as having upstream sediment wedges totalling 7000 m^3, and accounting for 38 % of the total bar sediment of 18, 400

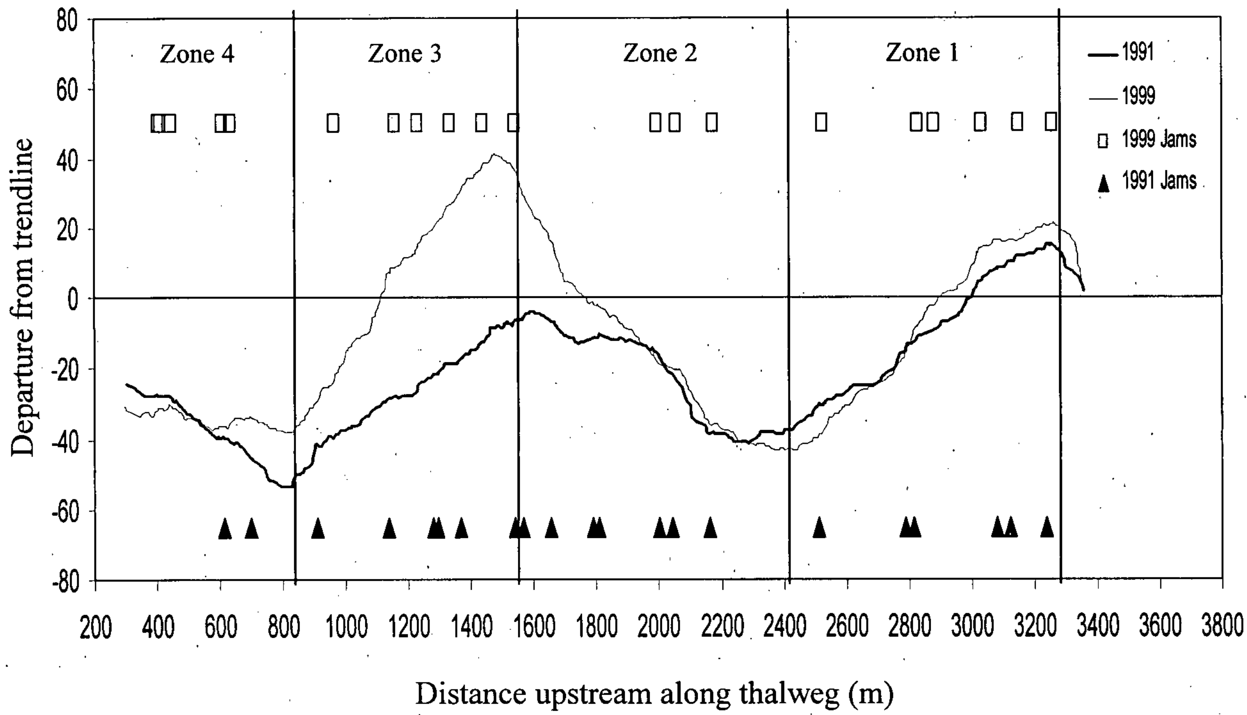
m^3. Nineteen of the jams that were associated with sediment wedges were the same for both survey years. In order to document the effect of the temporal aspect of jams and their sediment storage ability, storage associated with a particular jam in 1991 was subtracted by the storage associated with the same jam1999 to determine net erosion. Approximately 5800 m^3 of sediment was eroded from the upstream wedge behind the jams between 1991 and 1999; of this an additional 3100 m^3 was deposited at sites either immediately downstream of the jam or within jam complexes further downstream.

Cumulative Departure Plots

Cumulative departure plots were constructed to enable the identification of zones of either aggradation or degradation in the channel using data from the longitudinal profiles. For the plots to be interpreted from left to right, with positive slopes identifying zones of aggradation and negative slopes identifying zones of degradation, the calculation of cumulative departures had to begin at the upstream end of the profile. In addition to the cumulative departure plots, jams that were identified in the field as storing sediment were also identified in Figure 23. Because the plots for 1991 and 1999 follow the same general pattern of positive and negative slopes, the plots were divided into four zones that represented zones of sediment aggradation or degradation. The validation of the zones was done using field maps, bar and sediment calculations, ground-level field photographs and the low-level air photographs.

The positive slope exhibited by the plots in zone 1 identifies an aggradational zone (Figure 23). The channel located in the upper section of this zone is characterised by reaches that are partly confined by bedrock. The morphology within these constricted reaches are classified as straight

Figure 23. Cumulative departure plots for Carnation Creek, positive slopes indicating zones of aggradation and negative slopes indicating degradation. The location of all jams which were identified in the field as storing sediment upstream are also indicated. Zones 1and 3 are zones of aggradation. Zones 2 and 4 are zones of degradation.



chute channels and most of these reaches contain evidence of degraded bar remnants. SA VIII is located within zone 1 and in 1991 the wedge located upstream of the jam was still prominent along the right bank of the channel. In addition to the jam located in SA VIII, five other jams were identified as sediment storage sites in this zone. Even though most of these wedges were partly eroded and scoured following 1990 storm season, substantial volumes of sediment (> 5900 m^3) still remained upstream of these jams. In 1999, approximately 3800 m^3 of jam stored sediment still remained behind the same six jams responsible for the sediment storage in 1991. This section was likely an aggradational zone before the jams developed because it is located immediately downstream of the canyon. The location of this aggradational zone, according to the cumulative departure plot, begins inside the downstream end of zone 3 from Figure 3 and is therefore a zone of relatively lower shear stress in comparison to locations upstream due to the reduced gradient. The canyon has historically been a major source of sediment for Carnation Creek, for example the 1984 debris flow that originated in the canyon and sediment is initially deposited in this zone before being fluvially transported downstream. The slight concavity in both cumulative departure plots around 2700 m indicates the junction of tributary **C** (Figure 3) with the main stem (Figure 23). The departure of the 1999 plot downstream of 2700 m highlights increased sediment storage behind a jam over its previous 1991 levels (Figure 23).

The steepness of the slope exhibited by the 1999 plot is partly an artifact of using channel thalweg as a horizontal distance measure (Figure 23). As previously indicated in the examination of SA VIII, thalweg distance has been shown to dramatically increase upstream of a recently formed channel spanning jam. The smaller slope exhibited by the 1991 plot is, in part, the result of channel braiding on top of wedges that formed immediately upstream of jams. Increased sediment in this zone may have also resulted from a bank collapse in the vicinity of the final jam indicated in the figure, during the 1995 peak flow event (Figure 23). Evidence of this increased sedimentation downstream of the bank collapse was identified in the field during the 1999 survey.

The location of the inflection point between zone 1 and zone 2 in 1999 is approximately 200 m upstream of where it was in 1991 (Figure 23). The estimation of this distance is based on the establishment of the location of the inflection point in the 1999 channel and finding its similar position in the 1991 channel. By using this method it is estimated that with this method points can be located within plus or minus 15 m of their 'true' location in either the 1991 or 1999 longitudinal profile. The 200 m difference in the location of the inflection point in the 1991 and 1999 surveys is the result of two factors. The first factor was the presence of the large sediment wedge that was evident in the 1991 longitudinal profile plot (Figure 22a). As previously noted, the channel flowed below the surface of the wedge in 1991, hence the extension of the 'aggradation' zone downstream to include this portion of the channel. By 1999 the channel had migrated around the majority of the wedge although evidence of channel scour into the abandoned wedge face was noted during the 1999 survey. The second factor was a recently formed channel located within the vicinity of the 200 m difference in inflection points between 1991 and 1999. The new channel developed following a 1990 peak flow event that deposited > 1 m of gravel in the main channel, thus forcing the channel to avulse and re-route through a secondary channel. Consequently, by the time of the 1991 survey this 'new' channel was still scouring into the floodplain; an estimated 2200 m^3 of sediment was present in the 'new' channel during 1991 compared to < 1800 m^3 of sediment stored in same section in 1999 (Figure 23).

Zone 2 is identified as a degradational zone by the cumulative departure plots (Figure 23). The slope of the 1999 departure plot is much steeper than in the 1991 plot after 1950 m. It is hypothesised that the relatively steeper slope exhibited by the 1999 plot indicates increased sediment transport and/or degradation in the 1999 channel compared to the 1991 channel. The similarity of the 1991 plot to the 1999 plot between 1800 m and 1940 m is primarily due to three macro sized jams located between 1900 m to 2100 m (Figure 21a). Downstream of channel spanning jams that actively prevent sediment transport, channel scour downstream is expected. Such patterns are identified by the cumulative departure plots (Figure 23).

Downstream of 1800 m, the 1991 plot levels off and the 1999 plot continues to indicate channel degradation for another 300 m (Figure 23). The main difference between the two years appears to be the retention capacity of downstream jams. The flattening of the 1991 cumulative departure plot is due to the presence of jams that partially spanned the channel in the 1991 survey, but were absent by the 1999. The presence of these jams in the 1991 channel accounted for an additional 2000 m^3 of channel stored sediment. In 1991 the scour zone downstream of the three jams was not nearly as extensive as it was in 1999, and this is entirely related the sediment trapping efficiency of the downstream jams. Five jams present in the 1991 survey limited the extent of the degradational zone by establishing sites of sediment storage. The reason for the extended degradation zone in the 1999 plot is clear; in 1999 the five jams are no longer actively interrupting sediment transport, i.e., they are older and have broken down allowing sediment to be eroded and transported downstream. As a result, the degradational zone continues downstream until the next complex of jams is reached (Figure 23).

The next inflection point in the 1999 plot is located around 1500 m; the location of the 1991 inflection point is approximately 100 m upstream (Figure 23). The difference in the locations of the respective inflection points is tied to a complex of multiple jams. In 1991 these jams jointly accounted for a wedge that spanned 60 m upstream from their joint locations; its extent was greater than the bankfull channel. By 1999 remnants of the wedge were still found 60 m upstream of the jams, however, it had been significantly eroded over the 8 years and its extent was reduced to one half to two thirds of the bankfull channel. This erosion of the wedge was enough to extend the degradation zone 100 m downstream in the 1999 survey.

Zone 3 is identified in the plot as an aggradational zone (Figure 23). The steepness of the 1999 plot in comparison to the 1991 plot, is likely the due to deposition of the sediment eroded from the jams that were present in zone 2 during 1991 but were substantially eroded by 1999. Examination of the field maps and photographs revealed that the size of some of the wedges increased since 1991, some by as much as 500 m^3.

The location of the final inflection point is in almost the same for both plots (Figure 23). The area in which this inflection point occurs is located immediately upstream of B-weir. Upstream of the weir (during both surveys) is a long shallow pool that has become a long-term sediment storage site. The downstream zone (zone 4) for both survey years is characterised by long deep pools. The 1991 plot indicates channel degradation related to the lack of sediment storage sites provided by jams. In 1999, a number of jams had begun to act as sediment storage sites, thus the line is flatter.

The use of cumulative departure plots to identify zones of sediment aggradation or degradation along a longitudinal profile was explored in this section. The identification of zones of aggradation and degradation in the plot corresponded well with the morphological histories of those sections in the channel. In addition, the plot highlighted the importance that jams have in the short-term storage of sediment within the channel system and how changes in the ability of the jams to store sediment is translated downstream. This method may prove useful in tracing the movement of large sediment plugs through a system. At minimum the method will aid in the identification of zones where sediment plugs occur.

LWD Characteristics

The overall number of LWD pieces decreased over the length of channel surveyed from 2723 in 1991 to 1753 in 1999. This difference is in part due to differences in the estimation of the number of LWD pieces that comprised some of the larger jams in addition to pieces that were completely removed from the channel. LWD pieces were either completely removed from the system or were buried and not identified during the 1999 survey. The distributions of LWD diameters and lengths in Carnation Creek showed changes in the percentages of the five size classes between the 1991 and 1999 surveys (Table 5). During the 1991 survey, the second and third diameter size classes showed accounted for > 70 % of all LWD pieces, whereas in the 1999 survey the dominance of these two size classes decreased to < 60 %. For the length classes the smallest length class showed the highest percentages for both survey years, however, the 1991 percentage was much greater than the percentage in 1999.

The distributions for diameter and length of LWD were divided into those occurring as individual pieces and those occurring in jams (Table 5). The percentages for diameters of individual LWD pieces is fairly similar for both surveys, although the addition of a number of very large pieces is notable by the increase from 0.57 % to 6.00 % in size class 5. During the 1999 survey, and subsequently confirmed by the low level photographs, a number of old-growth cedar trees that had recently entered the channel after 1991 were noted. It is believed that these cedars are largely responsible for the noted increase. The effects of these gigantic organic debris (GOD) pieces (defined as LWD with diameter > 2 m and length > 30m) are also

Table 5. The distributions of the diameter and length of all LWD pieces, individual LWD pieces, and LWD pieces in jams.

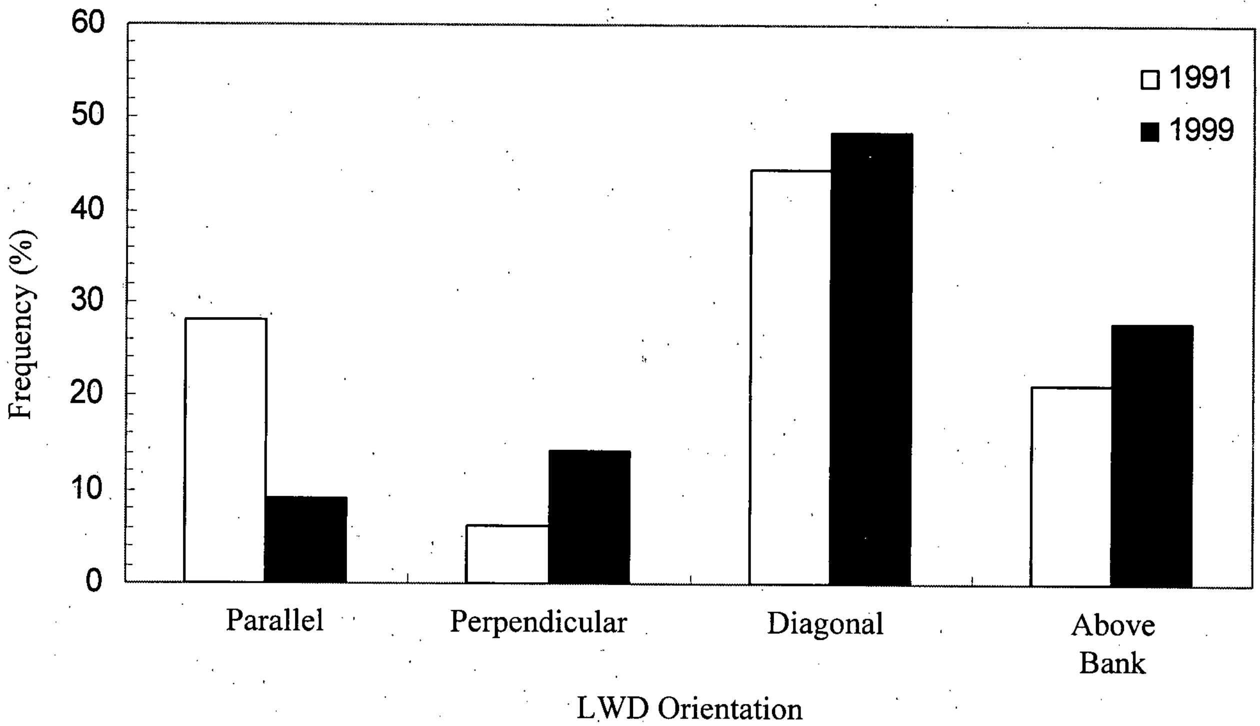
	All		Individual LWD		LWD in jams	
	%					
Diameter class	**1991**	**1999**	**1991**	**1999**	**1991**	**1999**
1	17.58	24.58	24.98	21.00	15.86	25.28
2	41.04	30.89	48.26	41.33	39.36	28.85
3	29.05	29.94	20.92	19.17	30.94	32.04
4	10.28	11.11	5.28	12.50	11.45	10.83
5	2.05	3.48	0.57	6.00	2.39	2.99
Length class						
1	67.35	39.79	82.94	42.83	63.73	39.20
2	19.80	31.93	11.22	26.83	21.80	32.92
3	7.31	17.66	3.58	18.17	8.18	17.57
4	4.79	7.54	1.41	6.00	5.57	7.84
5	0.75	3.08	0.85	6.17	0.72	2.47

seen by the increase in the percentage of length class 5. The length class distribution for individual pieces is very different for 1991 and 1999. Clearly the smallest length class dominates the 1991 data; at least seven times more frequent that the next class. In 1999 the smallest size class is still the most frequent accounting for 42 % of the observed LWD; it is only twice as frequent as the next class.

The distributions of LWD diameter and length classes occurring in jams are noticeably different between the 1991 and 1999 surveys (Table 5). Diameter class 2 shows the highest percentages in 1991 when compared to diameter class 3 in 1999. There is a 10% increase in the smallest diameter class in the 1999 survey; this may indicate an increase in the small number of pieces that comprised jams in 1999. The smallest length class comprises the highest percentage for the 1991 and 1999 surveys, however, short LWD pieces decreased by 24% with time.

The distributions of LWD diameter and length have changed between the two survey years. The general trend for all categories is an increase in the dominant size class. The change in the distribution for all pieces indicates that the smaller LWD is either being removed from Carnation Creek or being deposited above banks. Since there was little indication of extensive recruitment of LWD from the riparian zone, the larger more stable pieces are becoming the dominant size classes in the system. This suggests an increase in the overall stability of LWD between the two surveys. Abbe *et al.* (1993) suggested that the stability of LWD pieces is expected with ratios of D_{log}/d_c (LWD diameter divided by average depth of the channel) and L_{log}/w_c (LWD length divided by channel width) greater than 0.5 for Queets River, Washington. For Carnation Creek the average channel depth and width is 1.39 m and 17.07 m, respectively, in 1991 and 0.98 m and 17.91 m in 1999. Thus, any LWD in class 3 and larger for either the diameter or length size class would produce ratios greater than 0.5 and hence indicate a stable

Figure 24. The distribution of LWD orientation for all LWD pieces in Carnation Creek for the 1991 and 1999 surveys.



piece of LWD. The instability of the smaller size classes is especially evident by examining the distributions for individual pieces, with longer more stable pieces being more frequent in 1999 than they were in 1991. The increase in the small diameter category for LWD in jams illustrates how jams act as a sieve, collecting smaller less stable pieces when floated down from upstream. The number of pieces associated with jams in 1999 was 84 % compared to 77 % in 1991.

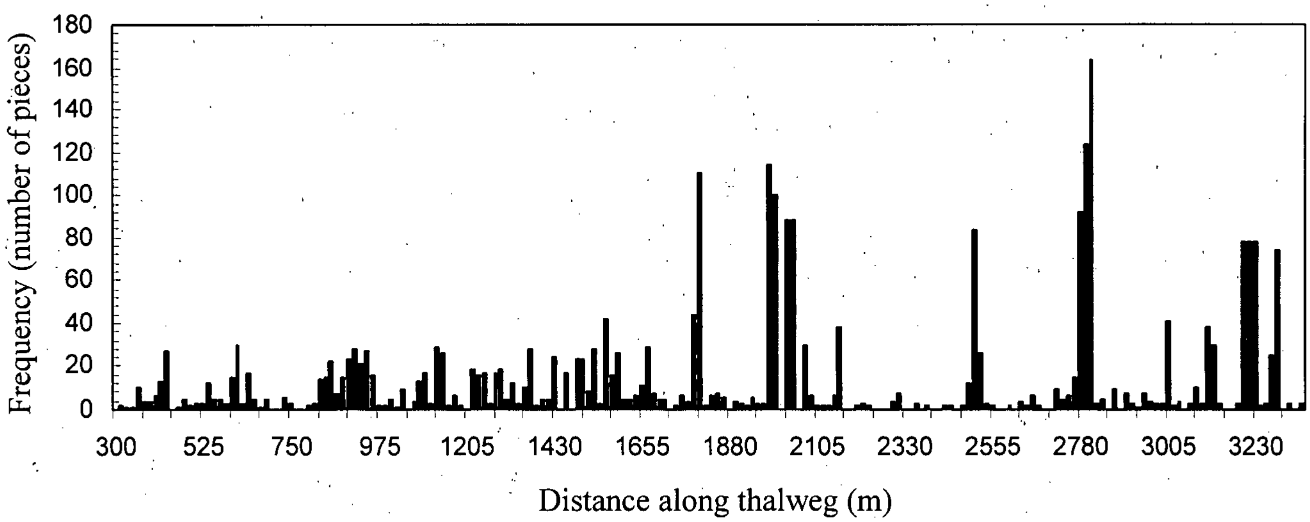
The change in the stability and functionality of LWD between the 1991 and 1999 surveys is further illustrated by the distribution of LWD orientation (Figure 24). LWD oriented either perpendicularly or diagonally has an increased influence on channel morphology and sediment transport over LWD that is oriented parallel to the channel (Hogan, 1987). A higher percentage of LWD pieces are oriented either perpendicularly or diagonally to the channel in 1999 than in 1991, indicating that LWD will have a greater influence on the channel in 1999 than in 1991 (Figure 24). The increase in the percentage of above bank LWD between the two surveys is related to the LWD pieces associated with jams that have been isolated from the channel.

The location of LWD in 15 m intervals along the channel for 1991 and 1999 is shown in Figure 25. The diagram also indirectly illustrates the distribution of jams throughout the 1991 and 1999 longitudinal profiles as sites with the highest frequency of LWD pieces. Major differences in the number of pieces between the two years are related to thalweg changes associated with jam age, as discussed previously.

Overall, the data indicates a trend towards increased stability in LWD between the two surveys as smaller less stable pieces are removed from Carnation Creek via fluvial processes or are trapped by more stable LWD structures.

Figure 25. Frequency distributions of LWD pieces in 15-m intervals along the longitudinal profile for: a) 1991 and b) 1999. Major differences in the number of pieces reflect the lengthening of the thalweg in areas of a jam over time, thus the same number of LWD pieces will be lower because they are spread out over a greater distance. Sites of with a large number of pieces indicate jams.

a) LWD distribution for 1991



b) LWD distribution for 1999

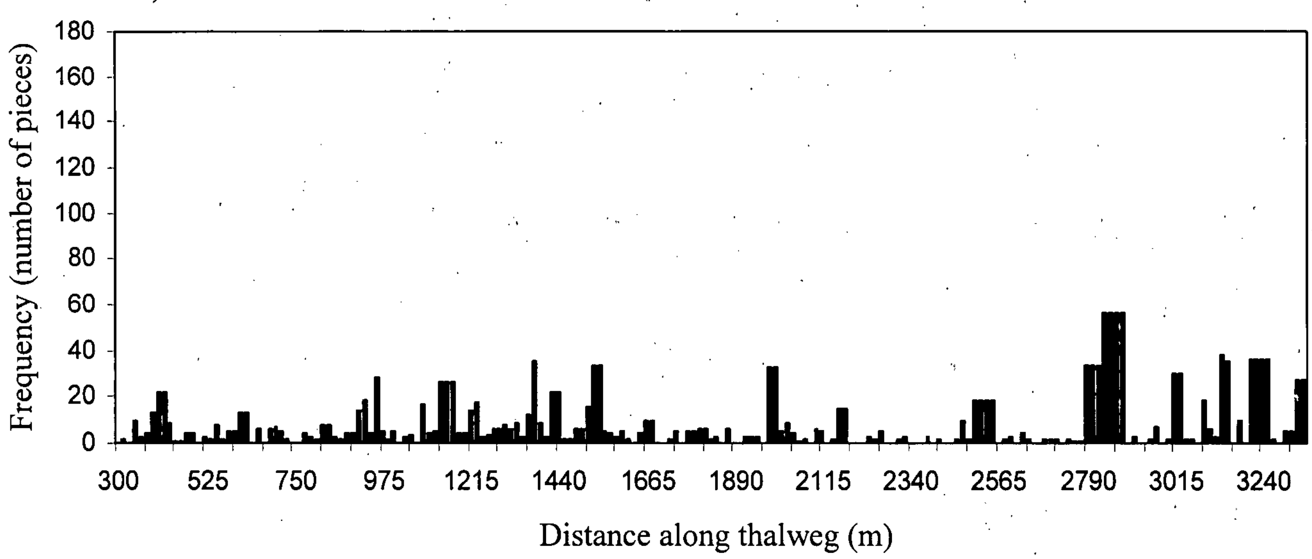
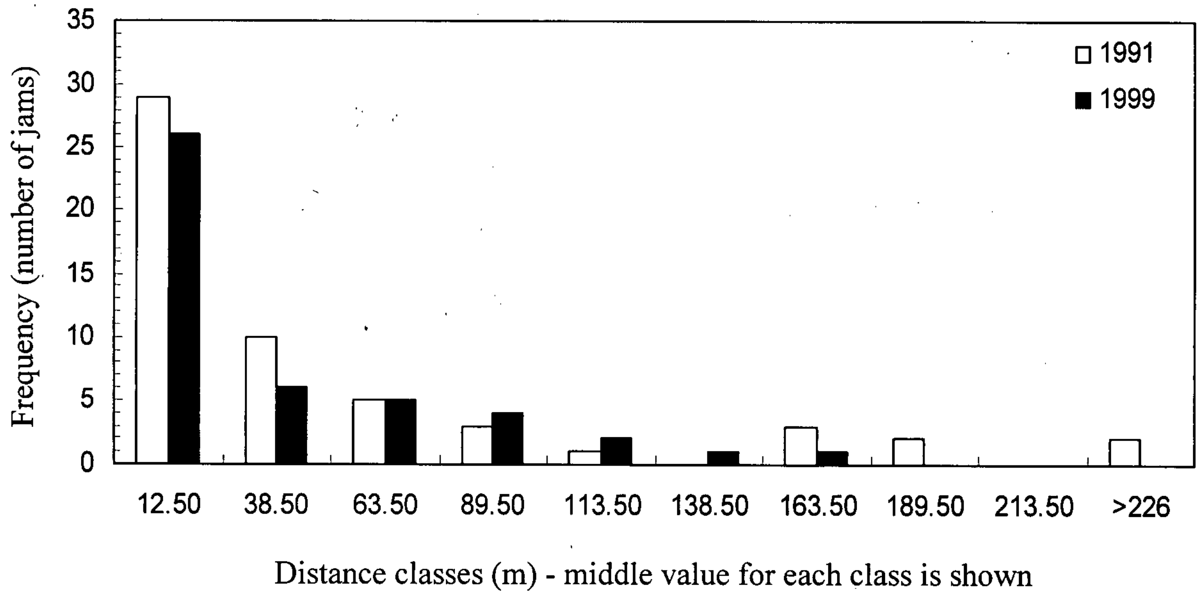
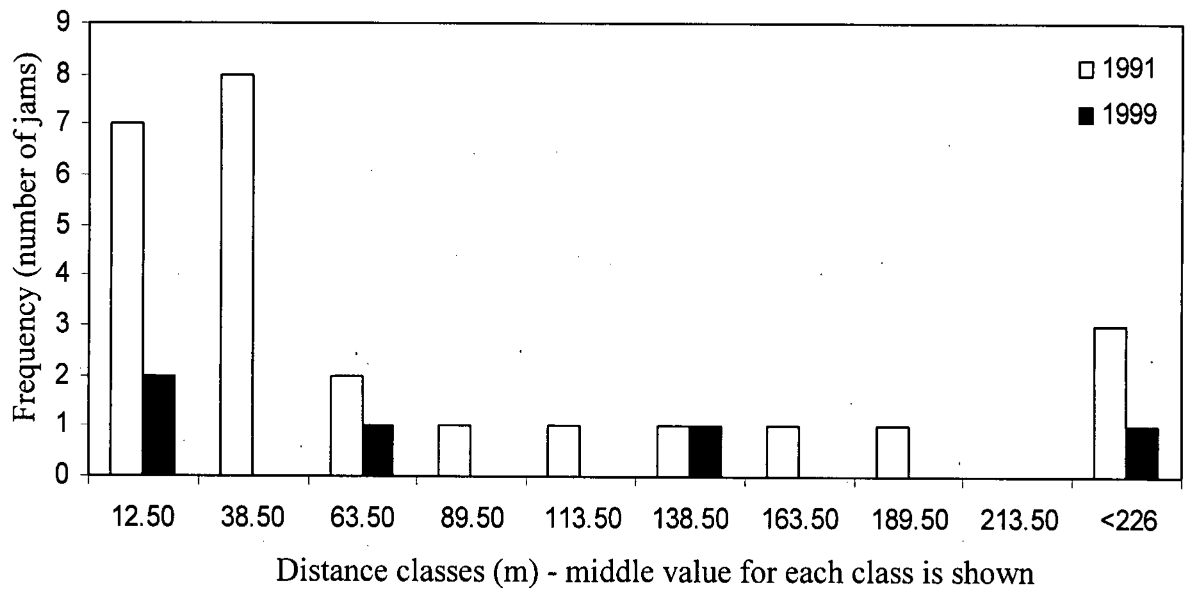


Figure 26. Jam spacing in meters for 1991 and 1999 for: a) all jams and b) all jams less than 10 years of age.

a) Jam spacing (m) for all jams



a) Jam spacing (m) for jams less than 10 years of age

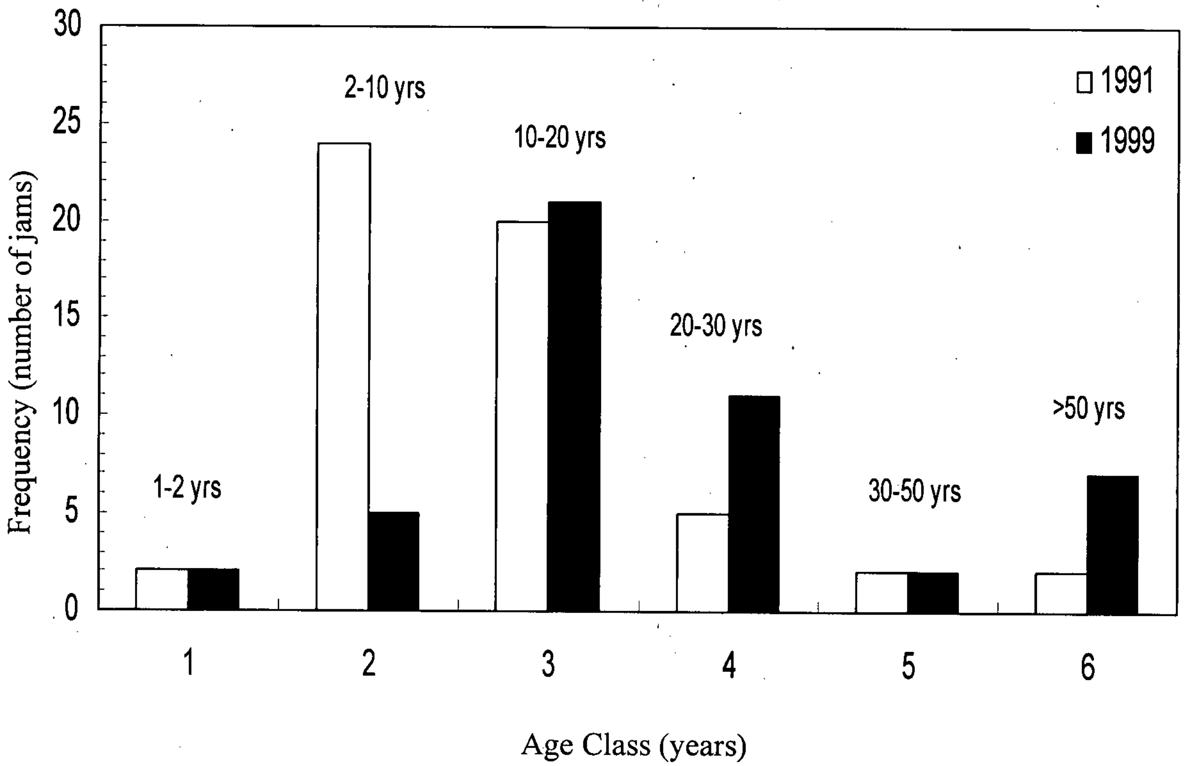


Jam Characteristics

More jams were observed during the 1991 survey than the 1999 survey, 55 and 48, respectively. Average jam spacing in 1991 was 2.84 w_b (48 m) with a range of 0.06 – 14.27 w_b, compared to 2.78 w_b (50 m) with a range of 0.11 – 18.31 w_b in 1999 (Figure 26a). However, it is the younger and larger jams that are important for sediment transport and storage. Re-examining the data and determining the spacing of jams that are less than 10 years old, another picture emerges: jam spacing was 6.34 w_b in 1991 and 18.36 w_b in 1999 (Figure 26b). It must be noted that after logging in the Carnation Creek watershed much of the LWD in the creek was logging-related. A majority of the old jams and many sites of newer jams are associated with old growth trees that entered the channel prior to the onset of logging.

The linear nearest neighbour statistic was used in order to test the presence of pattern in jam spacing. Values of 1.15 and 1.24 were obtained for all of the jams for 1991 and 1999. The value of 1.15 is not distinguishable from a completely random pattern according to Pinder and Witherick (1975). However, the 1999 value of 1.24 suggests a trend towards a regular pattern. It is hypothesised that a random, non-fluvially deposited, or regular, fluvially deposited, pattern in jam spacing emerges because jam formation is closely associated with major disturbances and, since these disturbances do not occur uniformly throughout the watershed, the overall pattern, i.e., for all jams in a system, may appear random. However, it is further hypothesised that jams formed during the same disturbance period will appear clumped. In order to test this hypothesis, the 1991 data was utilised since it was temporally more close to two major disturbances in Carnation Creek, logging and the 1984 peak flood. The distribution ratio of age class 2 jams in 1991 was 0.69 and therefore suggests a potential for clumping. Examination of age class 3 jams yielded a distribution ratio of 0.97 or nearly random.

Figure 27. Age distribution of jams for the 1991 and 1999 surveys.



Examining the age distribution of jams for each year highlights a few important points (Figure 27). First, jams are generally older in 1999 and therefore should have a lesser effect on channel morphology compared to 1991. Secondly, jam frequency appears to reflect periods of important geomorphic or disturbance events. Specifically, looking at the 1991 data, the 1984 storm is reflected in the high number of jams appearing in age class 2 and the onset of logging in the watershed is highlighted by the number of jams in age class 3 (Figure 27). Most of the logging-created jams appeared to have originated as single key pieces, that either fell into the stream during logging and were not removed or were blown down either during or immediately following logging (information obtained from the sequential low level air photographs). The resultant shift in ages in 1999 indicates no major channel disturbance occurred during the intervening survey period and that some of the jams completely disappeared as a result of natural decay processes or were removed during bankfull flow events (Figure 27).

Closer examination of Figure 27 reveals a discrepancy among the number of jams in each age class that cannot simply be explained by the shifting of classes as a result of the time between the two surveys. An analysis of the field notes and the low elevation photographs revealed three factors that contributed to these differences. First, a number of jams that were observed in 1991 had broken down by 1999, this included jams in most age classes. Second, some of the jams observed in the 1991 and 1999 surveys included LWD that was deposited at different times. If the newly deposited LWD changed the morphological influence of the jam on the channel, it was assigned the age of the newly deposited LWD. If, however, the newly deposited material did not alter jam and channel interaction significantly, the age of the jam remained the same. Much of the newer LWD in Carnation Creek is logging slash and unmerchantable timber and is therefore not as stable as LWD with boles or rootwads still attached. By 1999, some of this more recently deposited LWD had floated away from these older structures and the jam would therefore be aged differently. A third factor was the re-entrainment of buried jams. At least three jams noted in the 1999 survey that had not been identified in the 1991 survey. In these cases, field observations confirmed that changes in the channel planiform were responsible for exposing the once buried structures.

The jam size distribution highlights another important change in jam characteristics between the 1991 and 1999 surveys (Figure 28). The number of macro jams increased significantly and the number of micro jams decreased significantly in 1999. It is believed that in most cases the micro jams present during 1991 broke down and the LWD that comprised these jams floated downstream and collected forming larger more stable jams. At a number of jam sites in the 1999 survey, LWD that had been buried by large sediment wedges, had been recently excavated and subsequently deposited within the fabric of the downstream jam that had initially been responsible for the wedge that buried them. By 1999, most of the jam sites were associated with at least one key piece that originated from the old-growth forest. It is hypothesised that as these pieces rot and decay with time, jam frequency will continue to decline and the jam size distribution will continue to be more heavily skewed to the larger sized jam classes.

The distributions of individual jam characteristics were also examined for both the 1991 and 1999 surveys (Figure 29a). The distribution of jam height for both years is heavily skewed to larger heights, indicating that the height of most jams is at least ½ bankfull height (class 3) or greater (lower classes). A definite change in the distribution of the lateral extent or span of jams occurred between 1991 and 1999 (Figure 29b). Since the jams in Carnation Creek are lateral jams, their primary direction of growth is perpendicular with respect to flow; therefore it is expected that increases in jam size would be accompanied by increases in the lateral extent of

Figure 28. Jam size distribution. Jam size based on the jam classification procedure used during the field survey, refer to appendix 1 for details.

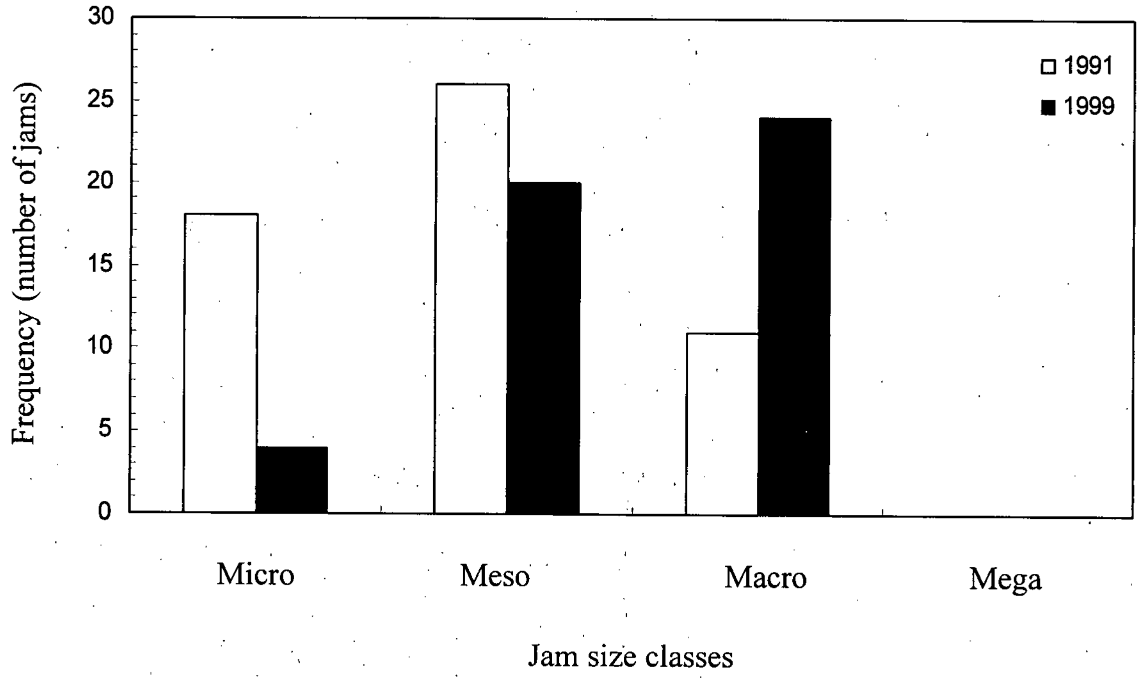


Figure 29. Distributions of jam characteristics for the 1991 and 1999 surveys, the following characteristics are shown: a) jam height, b) jam span, c) jam integrity, d) number of channel upstream of the jam, and e) sediment storage upstream of the jam. For specific details of class categories please refer to appendix 1.

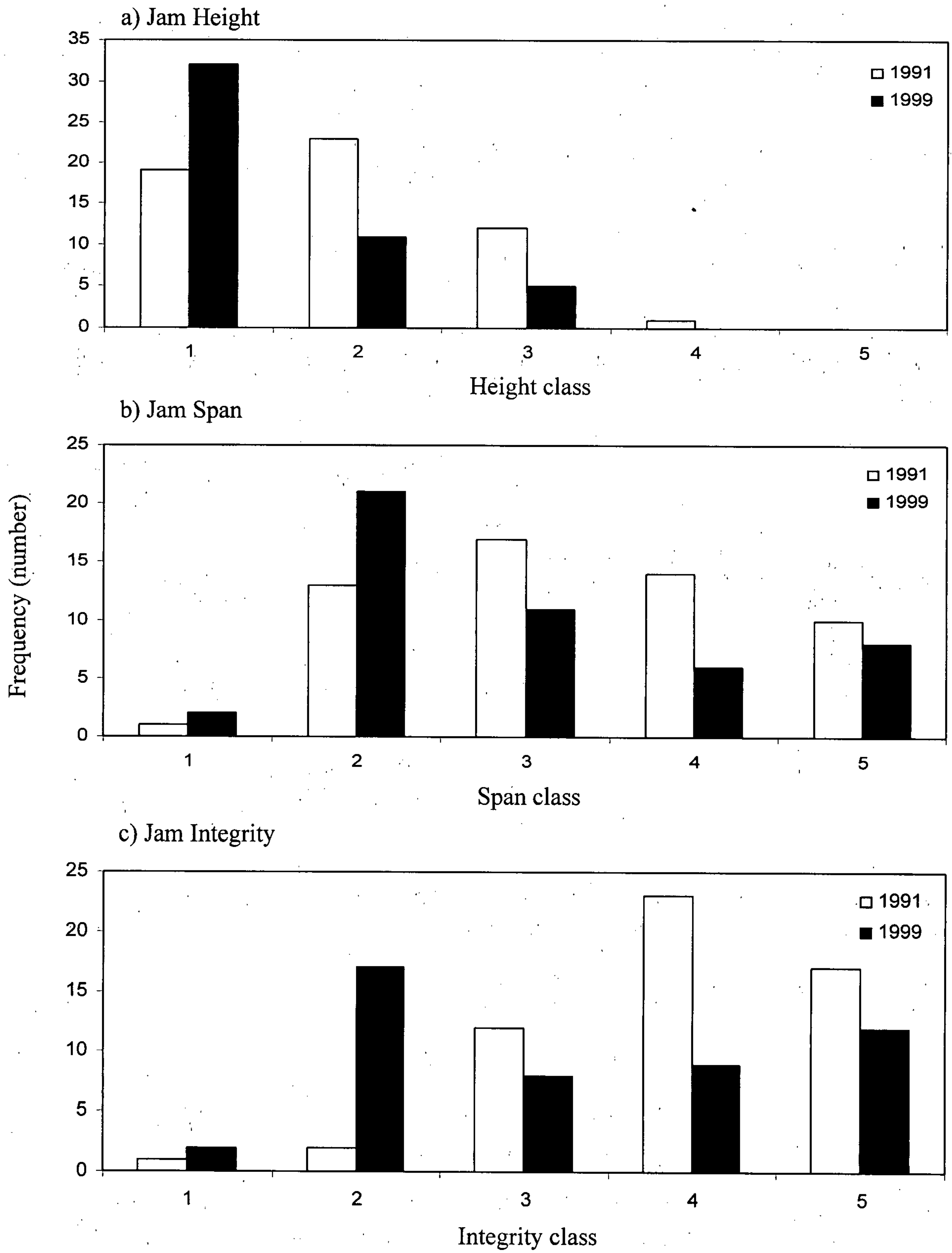
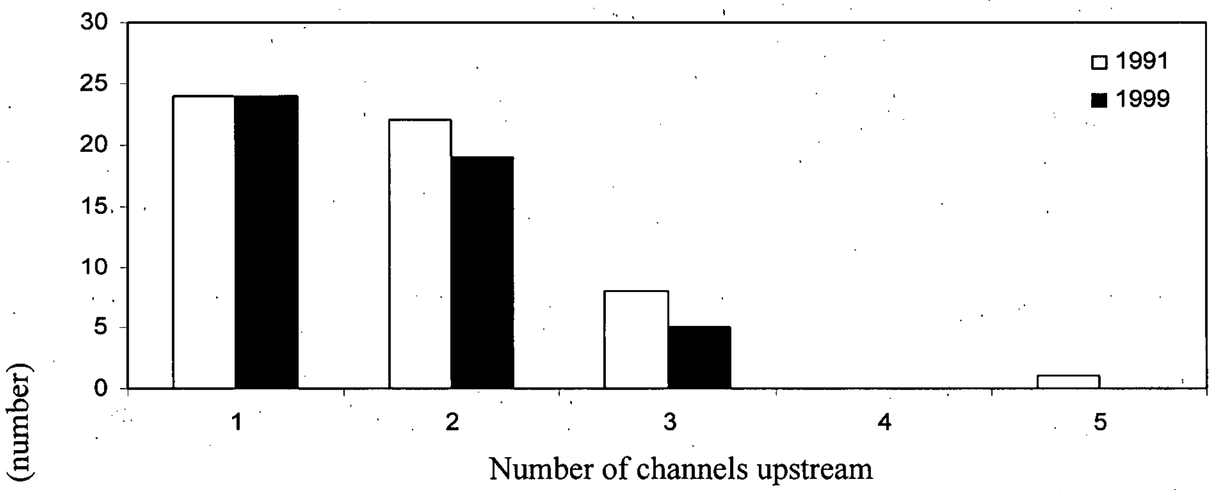
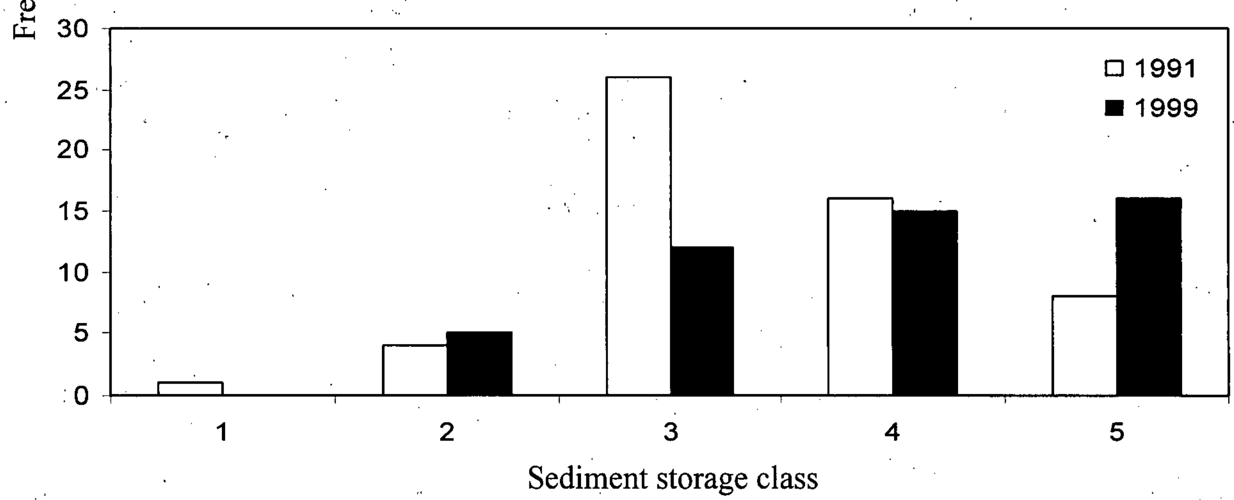


Figure 29. continued

d) Number of channels upstream of jam



e) Sediment storage upstream of a jam



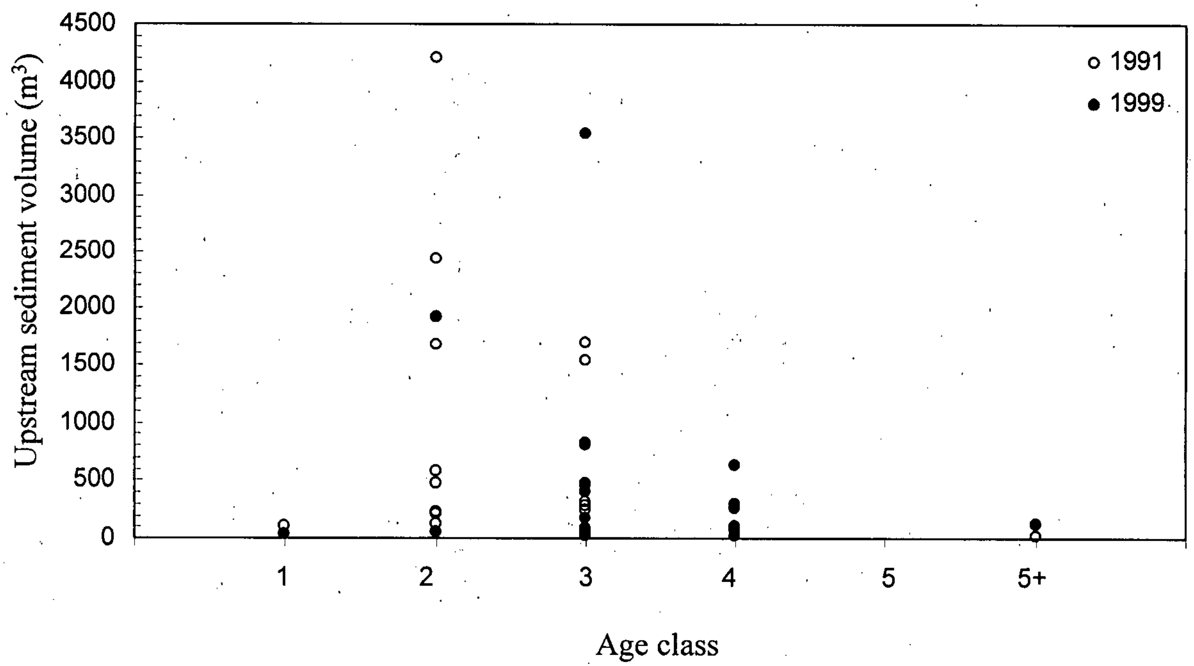
jams. There is an increase in the number of jams that either completely span the channel (class 1) or span greater than ¾ of the channel (class 2) in 1999. This shift further confirms the observed progression to larger sized jams.

The effect that jams have on channel morphology depends not only on their lateral extent, but on their integrity as well (Figure 29c). The integrity of jams in the 1991 plot is relatively low compared to the 1999 plot; it is believed that the 1990 storm compromised the integrity of the majority of the jams. Subsequent flood events during the 1990's induced the redistribution of in-channel LWD and have resulted in the increased jam integrity shown in 1999 (Figure 29c).

The number of channels upstream of a jam indicates the effect of the jam on channel flow patterns. If a large sediment wedge has accumulated upstream of a jam, for example, the channel may exhibit a braided pattern in the main stem or a number of flood channels would develop over bank. The distribution of the number of channels upstream of jams is almost identical for 1991 and 1999. The majority of jams in both years have 1 or 2 channels upstream (Figure 29d).

The distribution of the sediment storage characteristic of jams illustrates the changes jams have undergone during the eight years between the surveys (Figure 29e). Overall, the jams in 1991 stored more sediment than they did in 1999. It must be noted that this characteristic only accounts for the cross sectional dimension of sediment storage upstream of the jam and does not account for the longitudinal extent of the wedge. The distribution is understandable given that the integrity of most jams was substantially altered in 1991. The increased integrity that is exhibited by the 1999 jams has not yet been manifested in upstream sediment storage. This appears to be the result of either a reduced sediment supply in Carnation Creek or that there has been no significant flow event that has been able to redistribute large volumes of channel stored sediment after jam integrity had increased.

Figure 30. The age and relative sediment storage behind jams.



The temporal relationship between jam age and sediment storage is shown in Figure 30. Sediment storage used for this plot was the estimated wedge volumes from the longitudinal profile and cross sectional data. Jams in 1991 stored approximately 5200 m^3 more sediment than the 1999 jams. The jams holding the largest volumes of sediment were all less than 10 years old in 1991. By 1999 most of the large wedges had been substantially eroded or completely circumvented by the channel. Of the ten largest wedges approximately 6300 m^3 of sediment had been eroded by 1999 (Figure 30).

Overall the characteristics of jam have changed between the 1991 and 1999 surveys. These characteristics are expected to continue changing as the foundations of many of the older jams rot and decay.

LWD and Pool Characteristics

The longitudinal profiles were partitioned into pools, riffles, glides, runs, and log steps. The total length of each type is expressed as a percentage of the entire survey length for 1991 and 1999 (Table 6).

Pools are the most prevalent morphologic unit in Carnation Creek comprising over 65 and 56 % of the total survey length in 1991 and 1999. The percentage of riffles was nearly identical for the two survey years, however, the percentage of the channel classified as glides and runs both increased from 1991 to 1999 (Table 6). Glides and runs represent intermediate morphologies between pools and riffles (Hogan, 1986). The increases in both glides and runs reflect the filling in of both pools and riffles. This is to be expected since a number of jams have broken down from 1991 to 1999, resulting in the redistribution of sediment downstream. Combining the pools with glides and the riffles with runs indicates an increased percentage of

Table 6. Pool and riffle proportions, riffle-pool spacings (R/P-R/P), and pool spacings (P-P).

	1991		1999	
Channel Units	%			
Pool	65.53		56.30	
Riffle	25.53		26.85	
Glide	1.57		6.63	
Run	1.83		5.36	
Log Step	0.59		1.64	
Pool + Glide	67.10		62.94	
Riffle + Run	27.36		32.21	
	1991		**1999**	
Method 1[a]	2.57	2.45	2.02	1.85
Method 2[a]	4.58	4.49	3.56	3.22
Channel Unit Spacings				
R/P - R/P (m)	30.98		46.22	
R/P - R/P (W_b)	1.81		2.53	
R/P - R/P (15 m units)	2.06		3.08	
P - P (W_b)[b]	1.95		1.77	
P - P (15 units)[b]	2.21		2.13	

[a] Pool-riffle proportions calculated after Hogan (1986).

[b] P-P: pool spacings calculated after Montgomery *et al.* (1995).

riffle 'types' between the 1991 and 1999. The percentage of the channel classified as pools in Carnation Creek for both surveys was greater than the range reported by Hogan (1986) of 10 to 52 %. However, the Carnation Creek pool percentage fell within the range of 13 to 79 % reported for streams in northwest Washington (Beechie and Sibley, 1997).

Pool and riffle proportions were calculated using the methods used by Hogan (1986). The proportions were calculated for both pools and riffles as well as pools (glides) and riffle (runs). Pools constitute a significantly larger proportion of the stream than riffles for both survey years (Table 6). Although there is not a significant difference between the two years, the release of jam-related sediment decreased the relative length of pools to riffles in 1999.

Pool and riffle spacings and pool spacings were calculated by two methods (Table 6). The first method determined riffle-pool (R/P-R/P) spacings as the distance between stable alluvial morphologic units (Hogan *et al.*, 1998). Again, the difference between the two survey years is not significant, although the increased R/P-R/P spacing does reflect the increase in the percentage of the channel classified as glides. The second method calculated pool spacings by the method proposed by Montgomery *et al.* (1995). This method examines pool number in terms of channel widths per pool. The 1991 values for pool spacings (P-P) are very similar to the results of the R/P-R/P spacings determined above. The decrease in 1999 pool spacings, given the information from the R/P-R/P spacings, suggests that the pools are more numerous but shorter in 1999 compared to 1991 (Table 6). Overall the values for pool spacings in both years (1.81 to 2.53) are much lower than the typical values of 5 to 7 channel widths for unobstructed alluvial channels (Leopold and Wolman, 1957; Leopold *et al.*, 1964). These values are typical for ranges of pool spacings in forested streams of the Pacific Northwest (Montgomery *et al.*, 1995; Beechie and Sibley, 1997).

Maximum residual pool depth and pool length was analysed for each pool and then differentiated depending whether or not the pool was proximal to a jam, individual LWD pieces, free of obstructions, or influenced by bedrock (Table 7). Jams were by far the more dominant structural element in pools and were present in greater than 70 and 65 % of the pools during the 1991 and 1999 surveys, respectively. Individual LWD pieces were the dominant structural element in 26 and 19 % of all pools in 1991 and 1999, respectively (Table 7). In total, LWD was proximal to 97 and 84 % of all pools in Carnation Creek in 1991 and 1999, respectively. It must be noted that the association of the structural element (i.e., jam, LWD, bedrock) and the pool does not imply that the obstruction is a pool forming mechanism. What is implied is that the presence of the element has altered the pool geometry, such as changes in pool depth or length.

Of the jam proximate pools, more than 72 and 69 % were influenced by more than one jam. The increase in the percentage of free pools in the 1999 survey indicates a decrease in the number of individual pieces of LWD present in the channel. The percentage of intervals without any LWD increased from 18 % in 1991 to 34 % in 1999. The change in the number of intervals void of LWD in 1999 is reflected by the increase in the percentage of free pools, from 2 to 11 % from 1991 to 1999 (Table 7). A small increase in the number of pools associated with bedrock outcrops was the result of channel changes due to the presence of channel spanning jams that induced bank erosion, exposing the bedrock between the survey periods.

Mean maximum residual pool depth for all pools is not significantly different for the two survey years. The earlier conclusion from the analysis of riffle-pool and pool spacing that pools in 1999 were shorter than 1991 is confirmed (Table 7). Proximate jam pools show no change in the maximum residual pool depth, but there is a 6 m decrease in jam-proximate mean pool length

Table 7. Changes in maximum residual pool depths (Max RPD) and pool length for proximate jam pools, free pools, and bedrock pools.

		1991		1999	
		Max RPD	**Pool Length**	**Max RPD**	**Pool Length**
			m		
All:	*Mean*	0.48	21.24	0.51	16.41
	SD	0.36	15.58	0.38	10.65
	SE	0.04	1.62	0.04	1.09
	n	92	92	96	96
	Min	0.00	2.00	0.00	1.20
	Max	1.74	79.00	1.46	57.70
Jam:					
	Mean	0.51	20.55	0.51	14.65
	SD	0.38	16.71	0.37	10.24
	SE	0.05	2.07	0.05	1.29
	n	65	65	63	63
	Min	0.00	2.00	0.00	1.20
	Max	1.74	79.00	1.46	57.70
LWD:					
	Mean	0.42	23.75	0.54	18.36
	SD	0.28	12.42	0.41	12.01
	SE	0.06	2.54	0.10	2.83
	n	24	24	18	18
	Min	0.00	6.00	0.00	4.90
	Max	1.11	56.00	1.24	45.00
Free:					
	Mean	0.10	6.00	0.33	19.87
	SD	0.05	1.41	0.21	7.78
	SE	0.03	1.00	0.06	2.34
	n	2	2	11	11
	Min	0.06	5.00	0.02	12.60
	Max	0.13	7.00	0.71	40.00
Bedrock:					
	Mean	0.20	22.00	0.89	25.85
	SD	0.05	14.14	0.46	12.38
	SE	0.04	10.00	0.23	6.19
	n	2	2	4	4
	Min	0.17	12.00	0.41	14.80
	Max	0.24	32.00	1.41	41.20

	1991	1999
	%	
Jam Proximate Pools	70.65	65.98
LWD Pools	26.09	18.56
Free Pools	2.17	11.34
Bedrock	2.17	4.12
Pools with 1 or more jam in length	72.83	69.79
Pools with 1 jam in length	45.65	56.25
Pools with 2 jam in length	18.48	11.46
Pools with 3 jams in length	7.61	2.08
Pools with LWD in length	97.83	84.54
% intervals without LWD	17.65	33.99

in 1999. Characteristics of LWD pools changed between 1991 and 1999. The number of pools that were proximal to LWD pieces decreased from 24 in 1991 to 18 in 1999. This decrease resulted in an increase in mean residual pool depth from 0.42 m in 1991 to 0.54 in 1999. Pool lengths, however, decreased from 23.75 m in 1991 to 18.36 m in 1999 (Table 7).

Jams were found to be the dominant in-channel obstruction associated with pools in Carnation Creek. In the majority of jam-proximal pools, more than one jam occurred along the pool length. This complicated any detailed analysis of specific jam characteristics since one jam could not be clearly identified as altering pool characteristics.

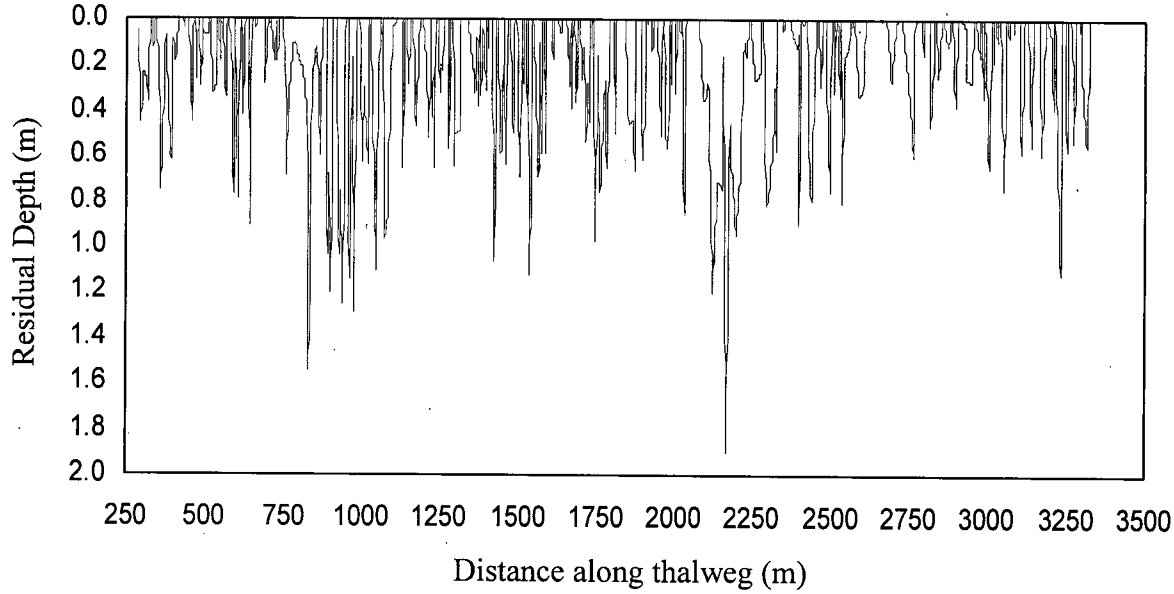
Residual Pool Depths

Plots of the residual depths for 1991 and 1999 are shown in Figure 31. The distributions of the residual pool depths were analysed for both survey years in an attempt to quantify the difference in the variability of the bed elevation between the two years. The resultant distributions of residual pool depths were not normally distributed (Kolmogorov-Smirnov test, $p < 0.0005$). Figure 32 presents the box plots of residual depths for 1991 and 1999. The mean and median values were almost identical for the two years, and the distributions for the two years were not significantly different from one another (Kolomogorov-Smirnov test). The values of residual depths in 1999 were not significantly different than in 1991 (Mann-Whitney test).

An investigation into the variance of bed elevation was evaluated using the standard deviation of the population of residual depths. However, the standard deviations for the two survey years were very similar. After close examination of the two longitudinal profiles it was believed that the standard deviations of residual depths should be more different between the two

Figure 31. Plots of residual depths for Carnation Creek for: a) 1991 and b) 1999

a) 1991



b) 1999

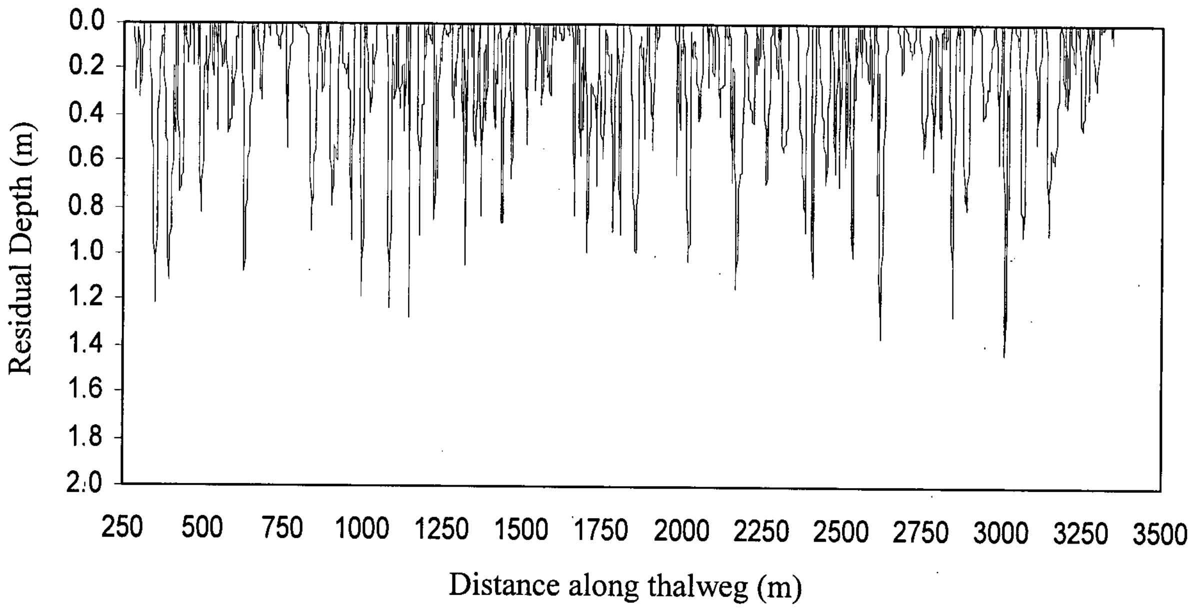
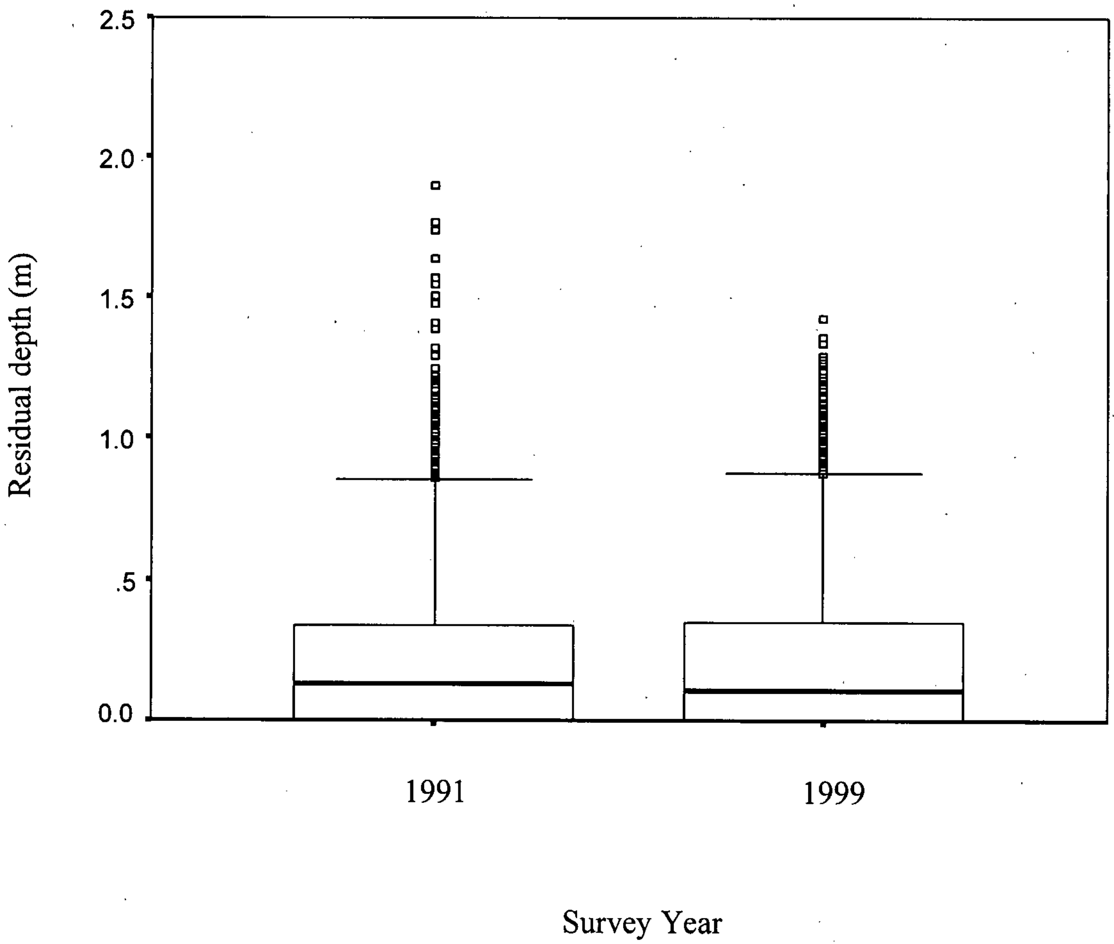


Figure 32. Box plots of residual depths for Carnation Creek for the 1991 and 1999 surveys. The upper and lower lines of the box are the 75 and 25 percentiles of the residual depth distribution (box length), the center boldline indicates the median values. The uppermost whisker is drawn from the upper line of the box to the largest point 1.5 box lengths away. Values that are greater than 1.5 interquartile ranges, but less than three interquartile ranges, are plotted as individual points.



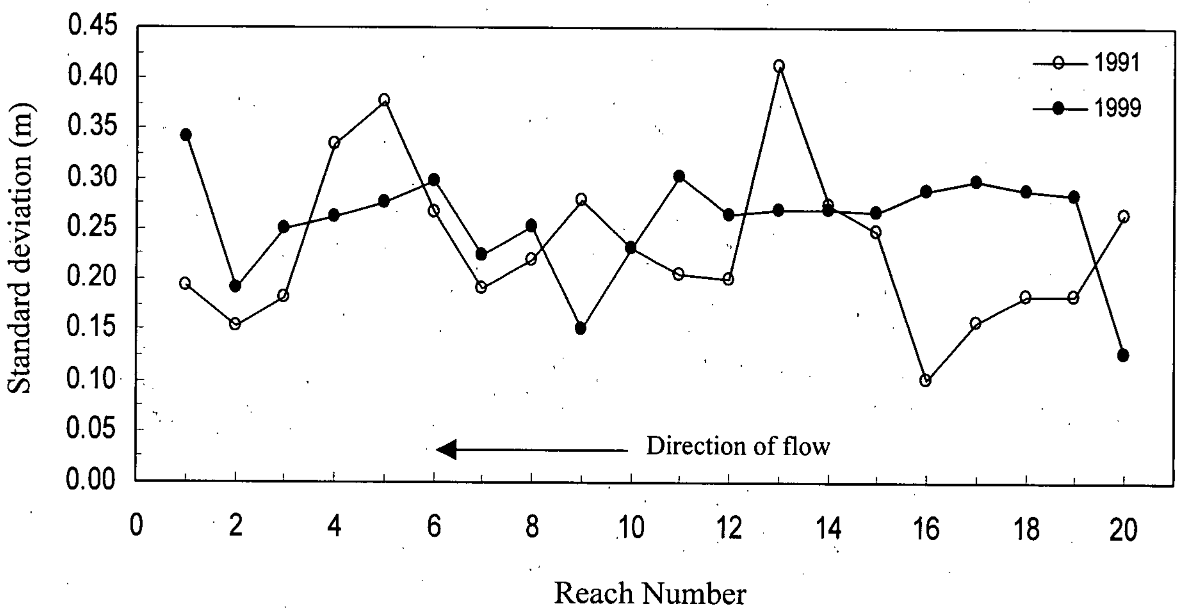
years than was shown by examining the entire distribution of residual depths. Whereas reach lengths in Madej's (1999) study ranged from 20 to 50 w_b, Carnation Creek was > 200 w_b for both surveys. The Carnation Creek data were then split into smaller sample sizes in order to evaluate the variance of bed elevations.

Firstly, the 1991 survey was divided into 20 'reaches' of 10 bankfull widths each. To make the comparison with the 1999 survey morphologically meaningful, the 1999 residual depth data were split with respect to the 1991 data. The locations of the start and end points for each of the 20 'reaches' from the 1991 data were located in the channel, then the channel locations in the 1991 survey were located to as best as possible to their channel location in the 1999 survey. Figure 33 presents the plot of the standard deviations of residual depths for the 20 'reaches' in the 1991 and 1999 surveys.

The distribution of variability in the standard deviations of residual depth is much different in 1991 than 1999 (Figure 33). The flattening of the curve for 1999 suggests increased stability, or at least, more uniform variation in residual depths. Most noticeable in the 1991 plot are high variabilities in reaches 4, 5 and 13, and the low variabilities in reaches 16 to 18. The reaches with lower standard deviations in 1991 compared to the 1999 values imply less variability, and therefore decreased morphological diversity.

Reaches 3 and 4 in Carnation Creek contain older LWD jams. These jams are no longer important in terms of sediment transport, but are important for habitat variability and pool characteristics (Figure 33). The variation of residual depths seems to substantiate this claim. The high variability in reach 13 in 1991 likely reflects the dominance of the entire reach by pools and not necessarily high morphologic variability. The largest pool in reach 13 was forced by the jam-related sediment wedge discussed earlier.

Figure 33. Variation in residual depths along the longitudinal profiles plotted as the standard deviation of residual depths for the twenty 10 w_b reaches in 1991 and 1999.



Reaches 16 to 18 are located in the vicinity of SA VIII, and it would be expected that variability in these sections would be lower in 1991 than they would be in 1999. Since the jam was breached in 1990 the released sediment produced a 'smoothing' effect on depth, especially downstream. SA VIII is located within reach 17, and the downstream effects of the erosion of the jam-related wedge during the 1990 storm, in terms of reduced variability in residual depths, extends at least 300 m downstream (reach 16) in 1991 (Figure 33).

The analysis of the distribution of residual depths did not reveal any significant change in the distribution of residual depths. However, this was due to the length of channel analysed. A more detailed analysis revealed that major differences in residual depth variabilities were related to locations of channel spanning jams and their related wedges.

Summary

In this section the longitudinal profile data were analysed. Firstly, jams affected channel morphology on a channel-wide scale and the extent of these effects depended on jam age. Younger jams have a dramatic effect on morphologic parameters and this influence lessens as a jam ages. Cumulative departure plots were used to explore zones of aggradation and degradation along the longitudinal profile of Carnation Creek and these zones, to a large degree, depended on the functioning ability of jams. Zones of sediment aggradation coincided with jam-related wedges and zones of degradation occurred either downstream of jams or in areas where jam-related wedges were being eroded. LWD characteristics changed during the two surveys (1991 and 1999) with larger pieces of LWD becoming more dominant as the smaller less stable pieces were either removed from the system or became masked in the matrix of a jam. Jam characteristics also changed between the two surveys. Linear nearest neighbour statistics were used to identify spatial patterns in the distributions of jams; it was found that even-aged jams occurred in clumps. This suggests that jam creation is related to large disturbances that effect localised segments of the channel.

Jams were also very important in terms of pools, occurring in the large majority of pools in Carnation Creek. Interpretation of specific jam-related changes to pool characteristics is confounded by the observation that more than one jam is commonly associated with a particular pool. The analysis of residual depths revealed that jams are an important factor in the variability of residual depths.

Proposed Model Of Jam Development In Unconfined Logged Streams

The model proposed by Hogan (1989) was developed from research undertaken in old-growth forested streams, thus the longevity of these jams would be expected to be much greater than those observed at Carnation Creek. Close examination of SA VIII has provided insights into the spatial and temporal dynamics of jam development in a logged environment. As a result, a new modified model is proposed based on the shorter temporal scales observed at Carnation Creek. Three phases have been identified:

1. 0-5yrs: Jam Adolescence – This phase begins after LWD has either accumulated upstream of a key member or is deposited as a result of a debris flow. A greater length of time may be required for additional LWD to accumulate behind the key member. A jam in this phase may not develop into a channel spanning structure, the development of which depends on the availability of LWD to the jam and the proximity of its formation to a peak flow event. LWD deposited by a debris flow may form a mature jam instantly and may not go through

this phase at all. Commonly, as shown in SA VIII, sediment is deposited along with LWD in a debris flow event. If a jam develops into a channel spanning structure and its interwoven matrix is sufficient to regulate sediment transport, it moves into the next jam development phase.

2. 5-10yrs: Jam Maturity – During this phase the effects of the jam on channel morphology are maximised. This is evident by extensive sediment accumulation upstream of the jam and downstream scouring. The channel adjusts by attempting to divert around the jam resulting in increased widths and decreased depths upstream. Downstream of the jam channel depth increases with little width variability and the channel bed can potentially scour to bedrock.

3. 10-15 + yrs: Jam Senescence – if the channel is unconfined it will attempt to laterally move around the jam; multiple channels are evident upstream cutting through the established sediment wedge. If the channel successfully migrates around the jam, the jam will likely remain isolated along the channel margins until the channel is diverted back to its original course. A jam is sometimes left elevated above the present channel and is abandoned on the bank as a result of extensive downcutting through the sediment wedge. The associated sediment wedge may also be abandoned and with time may eventually be colonised by riparian vegetation, creating a relatively long-term off-channel sediment storage site. A jam may also be partially broken down by peak flow events, leaving remnants of the jam in the channel to act as potential collection sites for in-channel floating LWD.

Conclusions

This study supports the general development scenario for LWD jams proposed by Hogan *et al.* (1998). Such a general pattern of jam development was observed at Carnation Creek, however, the temporal sequence was modified at this site as a result of logging. It is apparent that the ability of the channel to migrate around the jam influences the longevity of the interaction of the jam with channel morphology. Characteristics of the riparian zone and bank height may also influence this migration potential. Large, deep-rooted trees in the riparian corridor may reduce the chance of lateral channel migration around large jams, allowing them to increase in size as a result of jam-induced erosion patterns upstream. Lower banks promote lateral migration. More research is needed on the differences between morphological adjustments around jams in logged and unlogged streams on a temporal scale to elucidate long-term effects of logging on jam and channel development. The effectiveness of a jam, especially if formed by a non-debris flow related process, is at least partly dictated by the timing of a large peak flow event or a series of large events. These events re-organise the jam into a tighter, more composite matrix, frequently adding additional material to fill in the voids.

Inferring recurrence intervals of channel forming events based on the ages of jam structures may prove to be a useful tool when attempting to design forest road crossings in areas with inadequate peak flow records. The frequencies of large, morphologically important, peak flow events tend to be reflected in the age class distribution of jams. In managed forest areas such age distributions may also be better surrogates for culvert and bridge design than current discharge related criteria because they do specifically reflect LWD dynamics. LWD transport is a major cause of culvert and bridge failures and is ignored in typical peak flow analysis and related structural design. Such information may also provide planners with an approximate idea of the amount of sediment and debris volumes that the structure may have to accommodate during its lifetime.

The use of cumulative departure plots to identify zones of aggradation and degradation may provide a useful tool for managers to identify areas affected by increased or decreased sedimentation along the channel. Its use, however, is limited by the knowledge of the manager of the system in question. The cumulative departure plots further identified the importance of jams in controlling bedload transport in a stream system. Linkages between areas of aggradation and degradation were tied to jam-related sediment wedges and the subsequent erosion of these wedges with time.

Pool characteristics in Carnation Creek were controlled to a large extent by jams and LWD pieces. More research is required into the effects that jam aging has on specific pool characteristics.

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Appendix 1

This appendix is the version of the jam classification scheme developed by Hogan (1989) as it appeared in Hogan and Bird (1998). A log jam is defined as a major accumulations of debris or LWD that alters, or recently altered, channel morphology.

A. Log jam size and dimension for lateral jam (after Hogan and Bird, 1998)

Jam Size	LWD Volume/W_b^2 (m^3/m^2)	LWD Pieces/W_b^2 (n/m^2)	Height (D_b)[a]	Width (D_b)	Downstream influence[b] (W_b)
Mega	>1	>1	>1[c]	>2[d]	>100
Macro	0.1-1.0	0.1-1.0	>1	1-2	10-100
Meso	0.01-0.1	0.01-0.1	0.5-1.0	0.5-1.0	1-10
Micro	<0.01	<0.01	<0.5	<0.5	<1

[a] D_b = bankfull depth
[b] The upstream influence of a jam on channel morphology cannot be specified, as it depends on channel gradient and sediment supply conditions.
[c] Typically, does not exceed 2 D_b
[d] Typically, does not exceed 10 W_b

B. Log jam span characteristics (after Hogan, 1989)

Span (W_b)	
Complete:	
>1	Jam spans the channel and forms a dam. Water flows over the top or passes through the jam.
Incomplete:	
¾ -1	Jam spans the channel but is breached in one part of its span. Water flows around one or both ends or through the mid-section of the jam.
½-¾	Jam does not cross channel and is usually breached more than once. Water flows around one or both ends or through the mid-section of the jam.
¼-½	Jam is typically anchored on one bank or in the mid-channel. Water flows around one or both ends or through the mid-section of the jam.
<¼	Jam is typically anchored on one bank or in the mid-channel. Water flows around one or both ends of the jam.

C. Log jam height characteristics (after Hogan, 1989)

Height (D_b)	
Complete:	
>1	Jam is higher than local average bank height. The channel may be forced around the jam and into the riparian areas.
Incomplete:	
¾ -1	Jam does not exceed local average bank height (although individual LWD pieces in the jam maybe resting on the channel banks).
½-¾	Jam structure is prominent in the channel.
¼-½	Bar tops may exceed jam top. Jam is usually not capable of forcing the channel into the riparian area.
<¼	Bar tops exceed jam top. Individual LWD pieces in the jam may be buried by advancing bedload.

D. Log jam integrity characteristics (after Hogan, 1989)

Integrity	Jam Characteristics
Very solid	Very compact, strong LWD pieces (no rot). Largest LWD pieces have diameter ≥ 1 D_b and lengths ≥ 1 W_b. Stable and large anchors present (e.g. root wads and bedrock). Pieces are very tightly packed together and compact (with little if any void spaces between the pieces).
Solid	Compact, strong LWD, but smaller individual pieces (largest pieces have diameter ~ 1 D_b and lengths ~ ¾ W_b). Jam is anchored but overall stability is reduced. Minor voids exist between the debris pieces.
Weak	Predominantly small LWD pieces; larger LWD pieces are generally rotten. Jam has either a poor or precarious anchor. Large voids exist and pieces are loosely packed.
Very weak	Very small pieces with no apparent anchor. Jam is in transition (i.e., it is difficult to determine if a jam exists). The pieces are very loosely packed and large voids exist between debris pieces.

E. Sediment storage characteristics upstream of a log jam (after Hogan, 1989).

Amount of wedge excavated	Wedge characteristics
None	The channel zone is full of sediment (for example, sediment is filled to the top of the jam and extends completely across the channel). Sediment extends upstream as a function of channel gradient and sediment supply conditions, or until the next debris jam. Active overbank sedimentation in the riparian area is often apparent.
< 1/4	The initiation of one or more preferred channels through or around a jam begins to excavate the wedge surface. Active overbank sedimentation in the riparian area may occur during moderate flows.
1/4 - 1/2	A channel(s) has incised into the wedge surface. Relatively large volumes of sediment are stored near the jam or in areas of low shear stress. Active overbank sedimentation in the riparian area is unlikely except during high flows.
1/2 - 3/4	Preferred channel(s) have developed and a portion of the wedge may be colonized by riparian vegetation (primarily Alnus rubra (red alder) in coastal British Columbia).
> 3/4	Remnants of the wedge exist, but are difficult to identify and distinguish from the normal development of channel bars. Riparian vegetation may be colonized any remaining stable portions of the wedge.

F. Channel characteristics associated with log jams (after Hogan, 1989).

Number of channels	Channel characteristics
1	A single, preferred channel has established through or around a jam and incised into the sediment wedge. There are no flood channels.
2	A single, preferred channel has established through or around a jam and incised into the sediment wedge. A secondary channel around the jam or a flood channel through the riparian area has also developed.
3	One or two preferred channels have established through or around a jam. A secondary channel(s) around the jam or a flood channel(s) through the riparian area have also developed. The channel may be anastomosed around stable, vegetated portions of the sediment wedge.
>3	Preferred channels have established through or around a jam. Secondary channels around the jam or a flood channel through the riparian area may have also developed. The channel may be anastomosed around stable, vegetated portions of the sediment wedge.

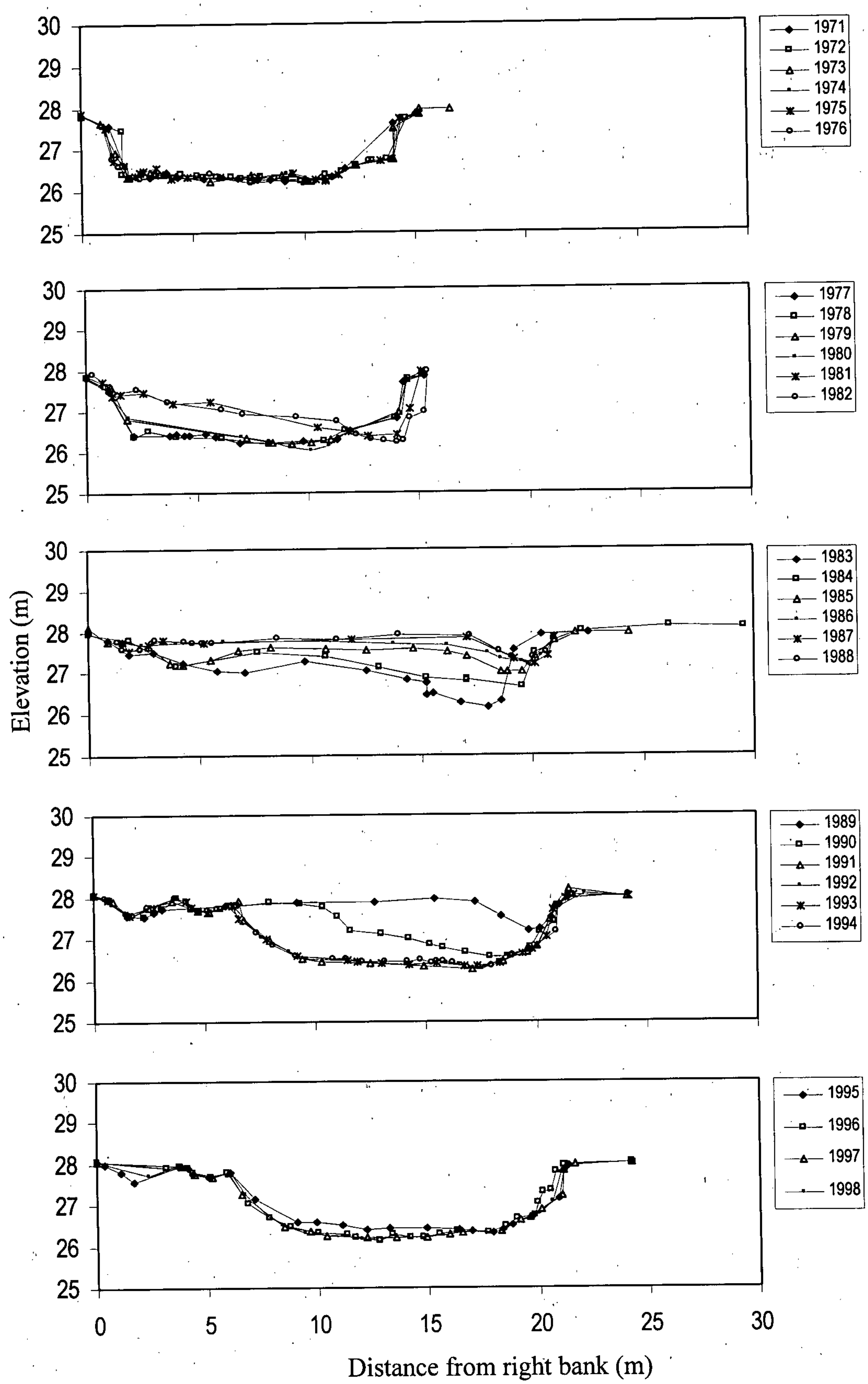
G. Log jam age classes (after Hogan, 1989). Five stages of channel adjustment following the formation of a log jam, corresponding to the age classes below, are reviewed by Hogan et. al., (this volume). Note below, however, that the <10 year stage of channel adjustment has been divided into two categories.

Time since jam formation (yr.)	Jam, nurse tree, and sediment wedge characteristics
<2	Primarily new LWD pieces (bark, branches, etc., remain intact). Includes new debris from upstream and upslope, apparently formed during the last major storm or landslide event. No nursed trees; the wedge is non-vegetated.
2-10	LWD pieces have lost some bark and few branches remain. Twigs are absent. Nursed trees (usually red alder in coastal British Columbia) are less than five meters high and are aged in the field (cut and rings counted). Any stable portions of the sediment wedge support a dense pioneering canopy of red alder.
10-20	Bark is absent from some LWD pieces but remains intact on others. Branches are generally absent. Nursed trees are between 10 and 20 years old (aged by increment cores). Natural thinning of the riparian canopy growing on the sediment wedge is evident.
20-30	Sapwood is soft; moss may cover a portion of stable LWD pieces. Nursed trees are 20 to 30 years old. Stable portions of the sediment wedge support grasses, herbs, and mosses in the understorey.
30-50	Bark is absent or sloughing; LWD pieces are stained and discoloured. Nursed trees are 30 to 50 years old. The colonized portion of the sediment wedge is difficult to distinguish from the adjacent riparian area.

Appendix 2

The additional data for the entire SA VIII section: XS 1 – XS 18; and SA VII: XS 1 to XS 4 for all variables discussed.

SA 8 Cross Section 1 Annual Plots



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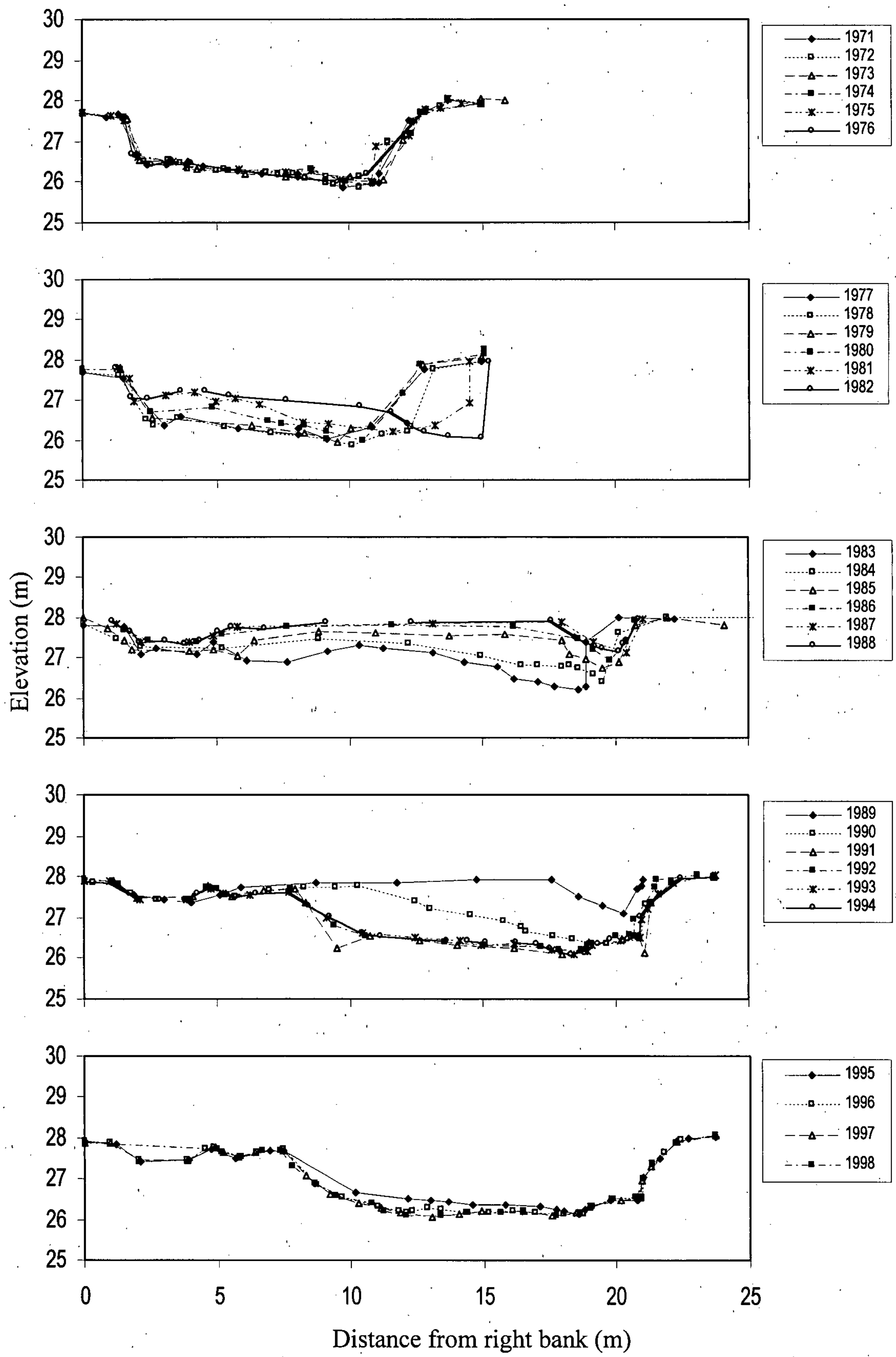

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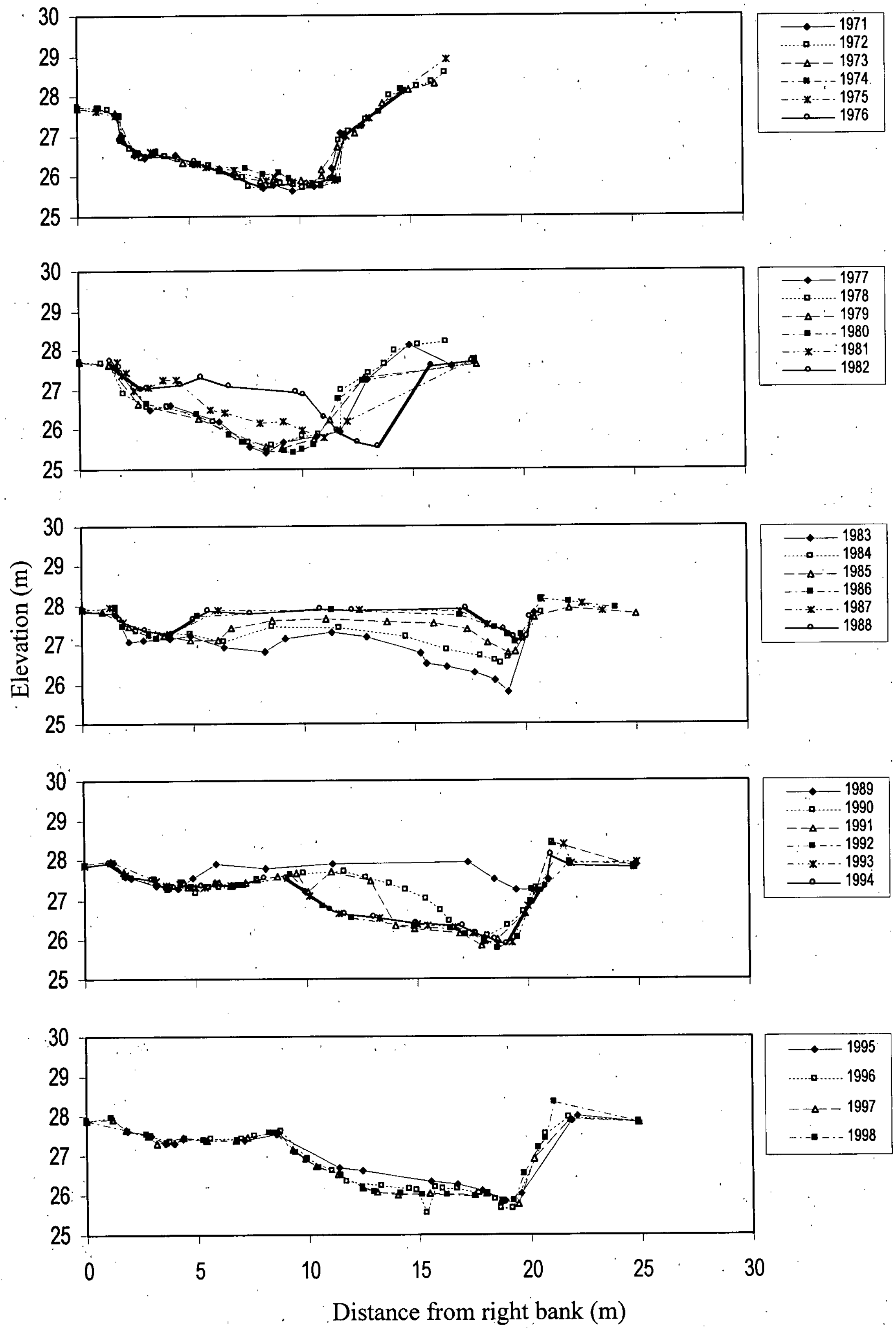

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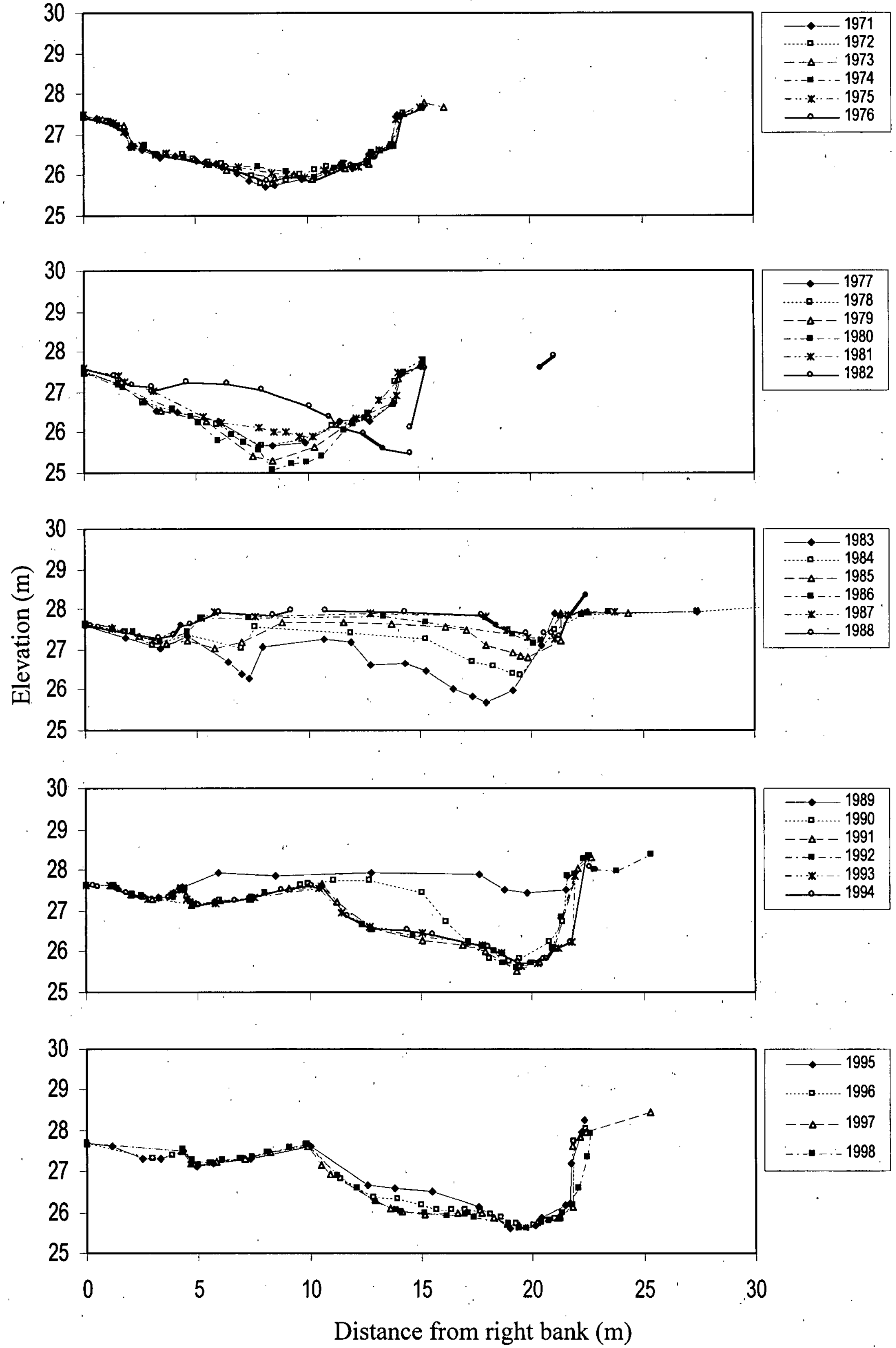

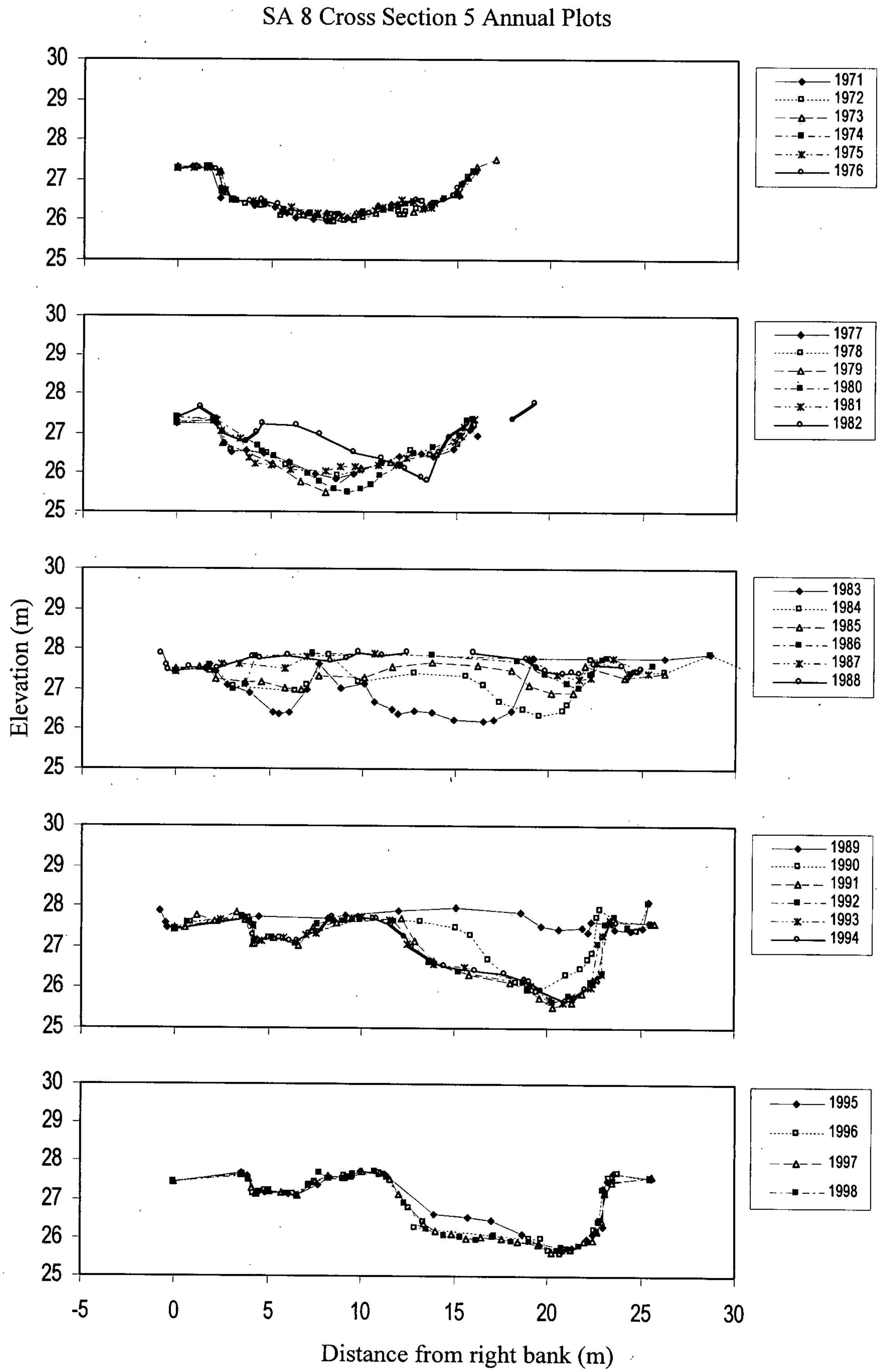
SA 8 Cross Section 5 Annual Plots
Elevation (m)
Distance from right bank (m)
30
29
28
27
26
25
-5
0
5
10
15
20
25
30
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
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1990
1991
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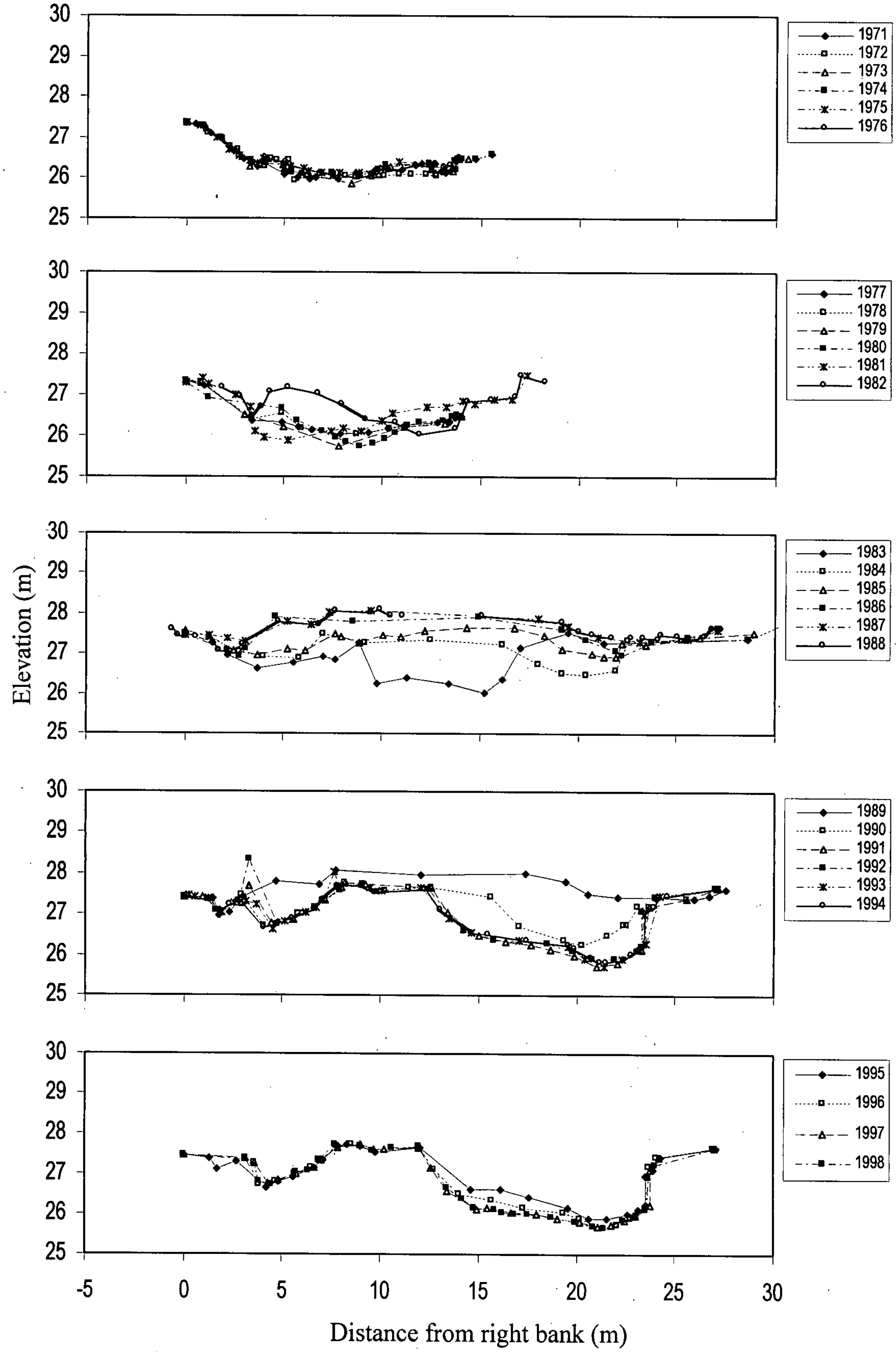
1996
1997
1998

SA 8 Cross Section 6 Annual Plots



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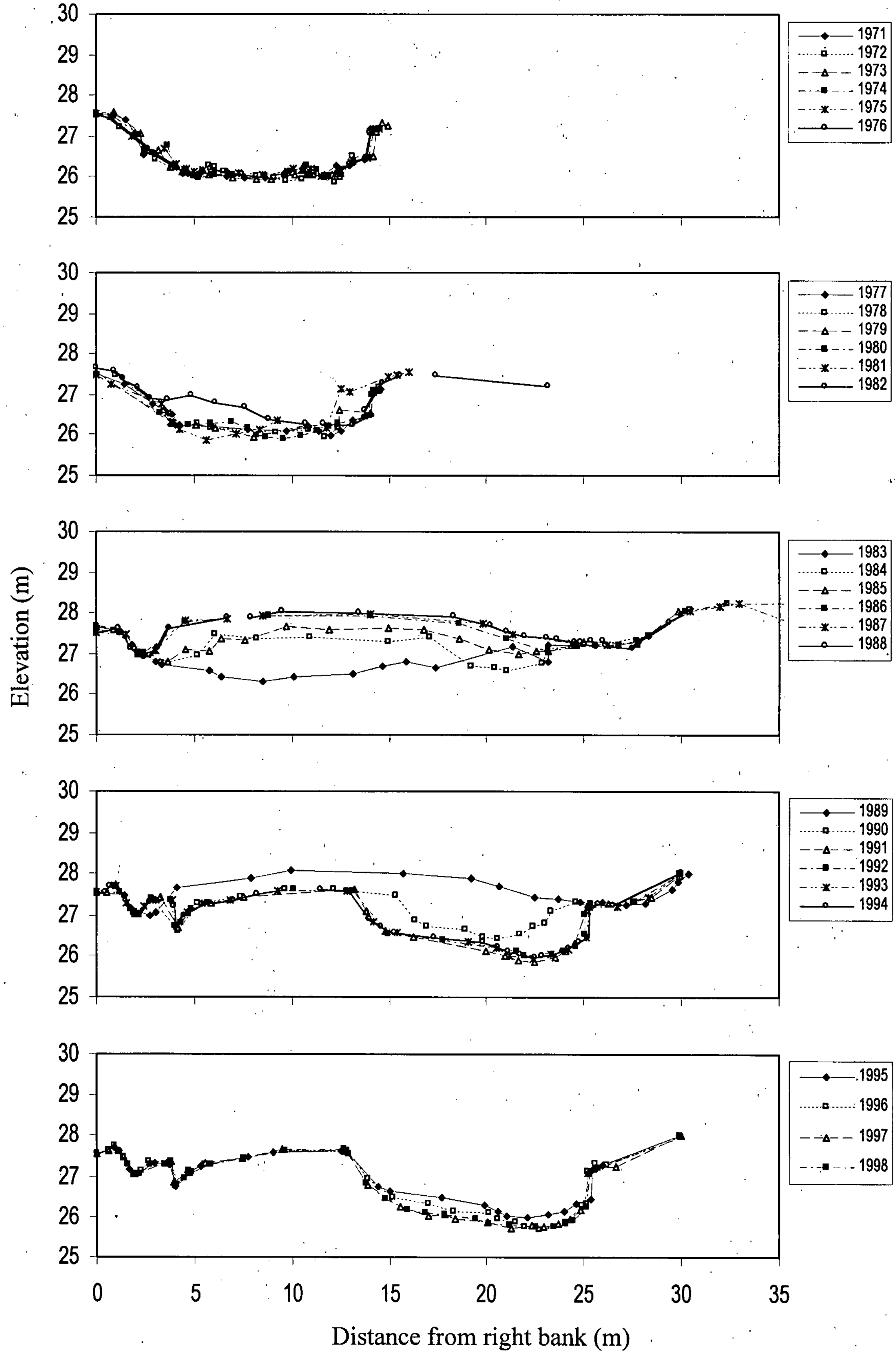
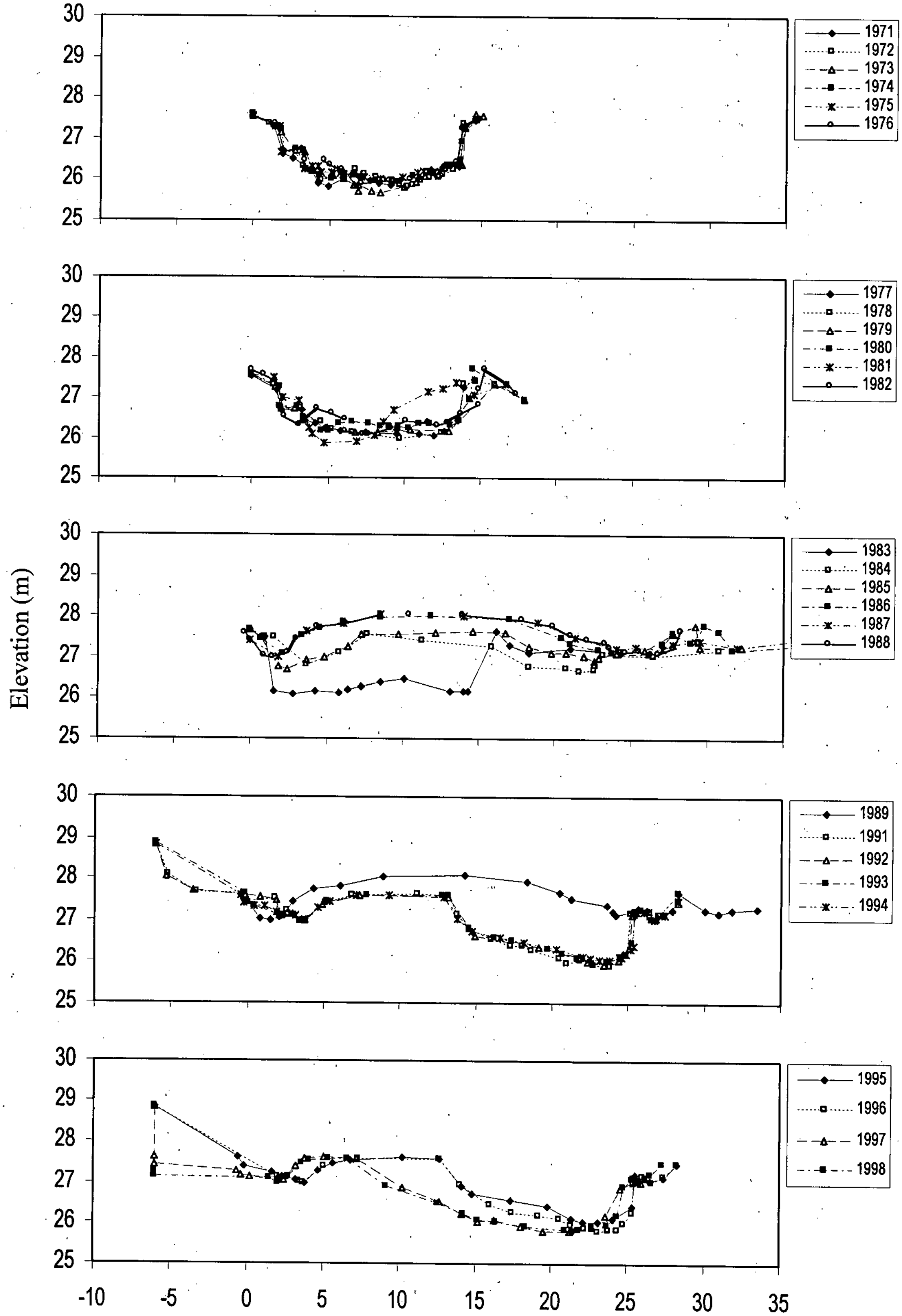
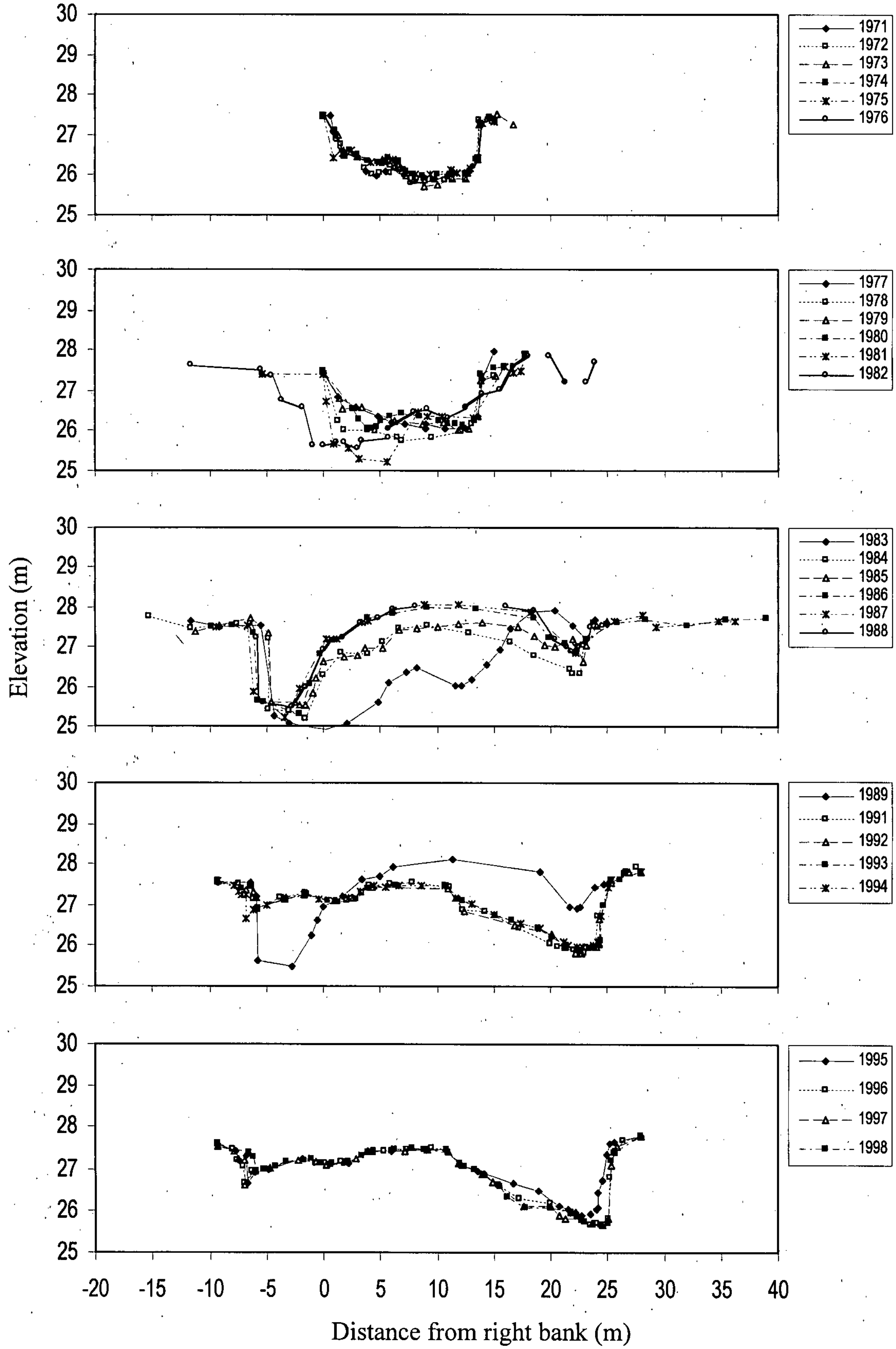


SA 8 Cross Section 8 Annual Plots



Distance from right bank (m)

SA 8 Cross Section 9 Annual Plots



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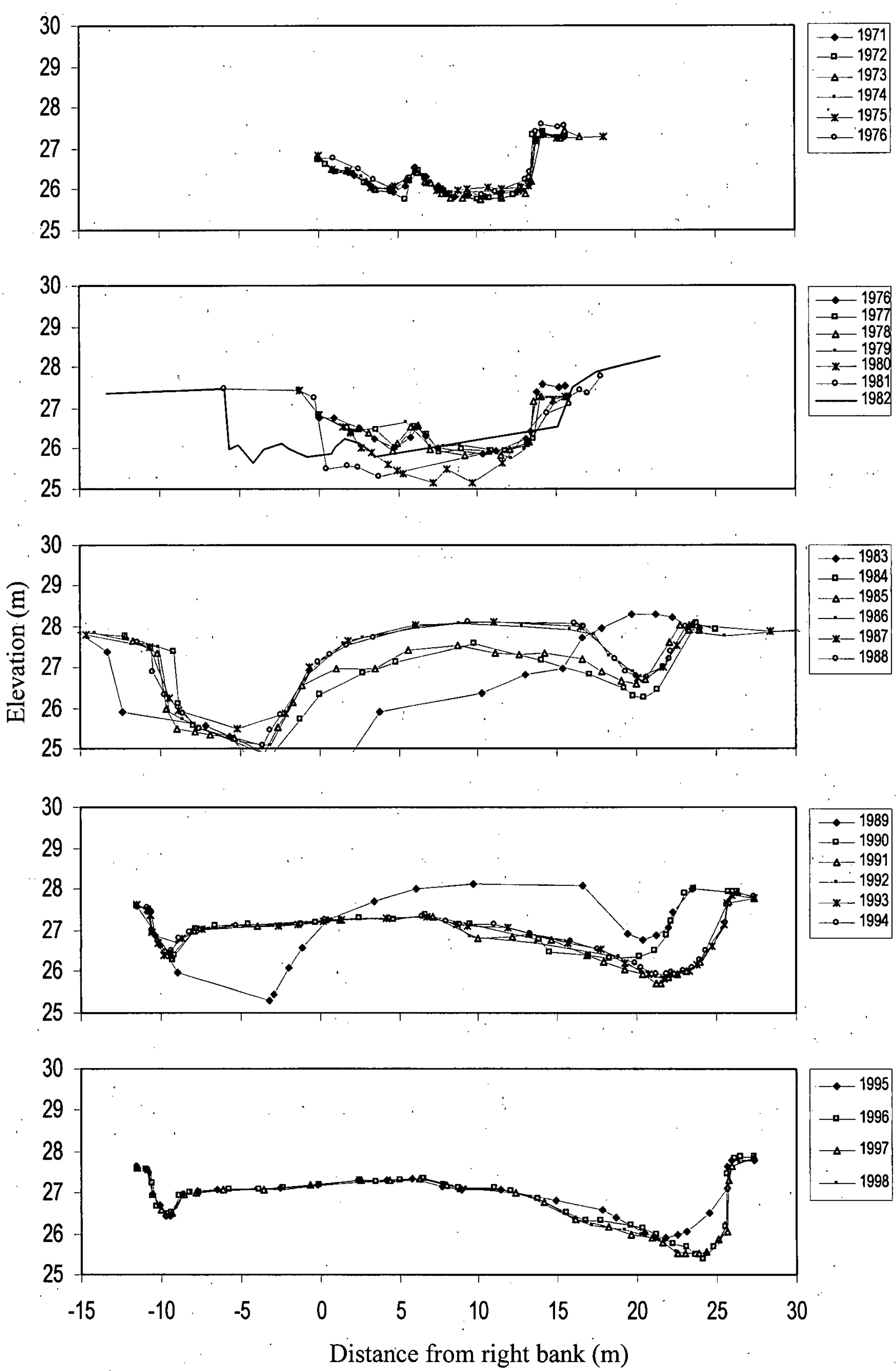

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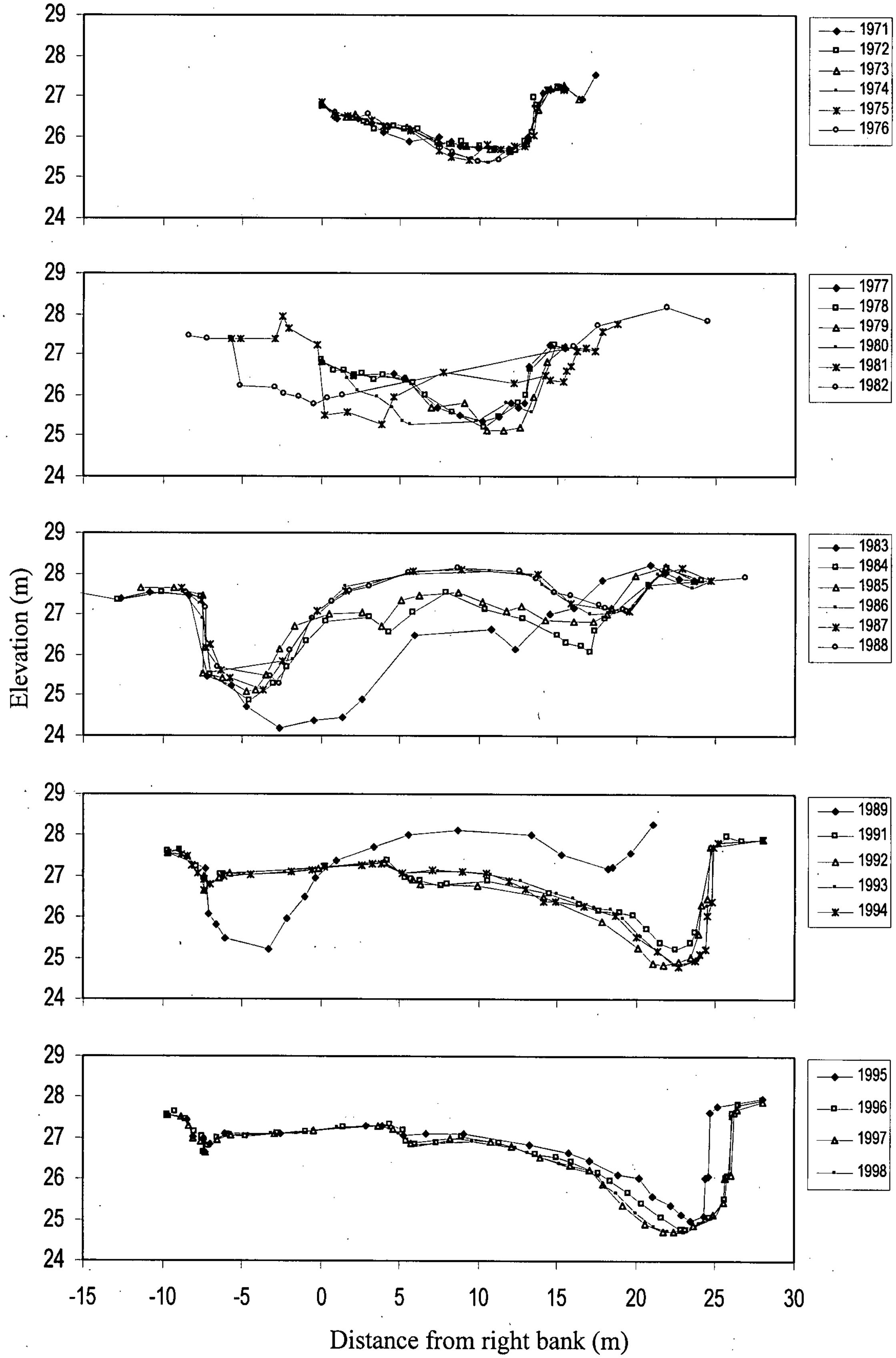

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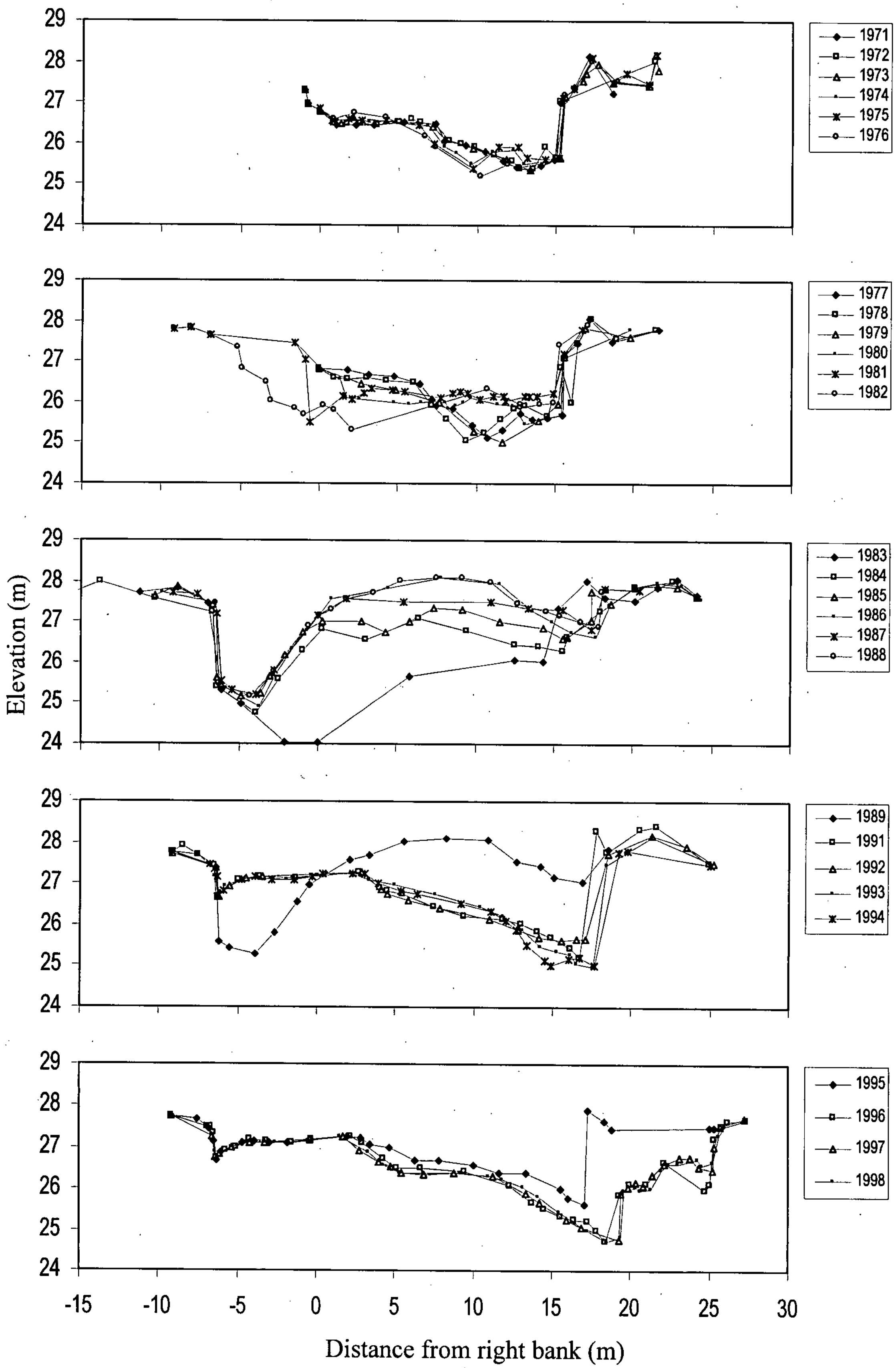
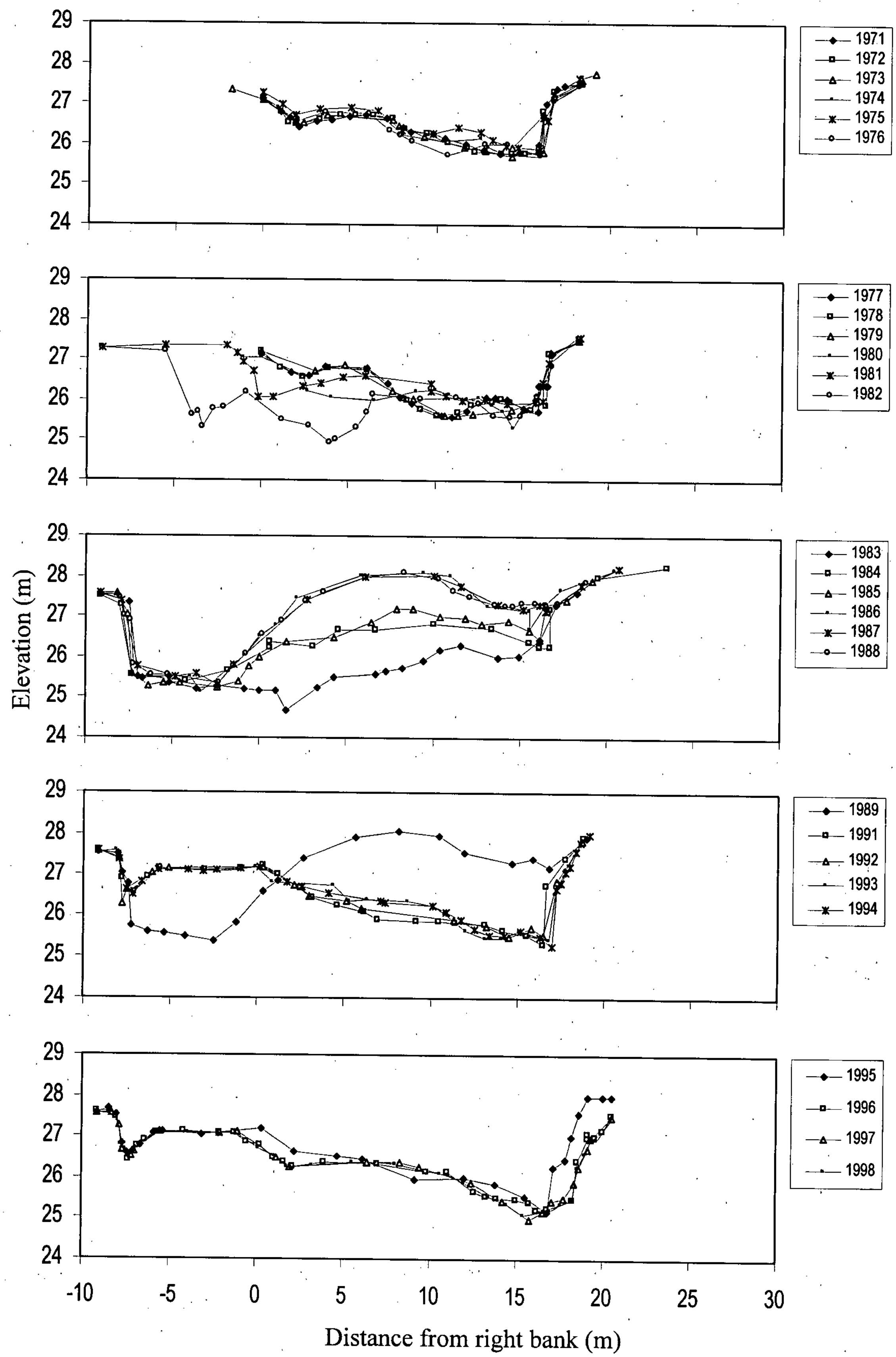


SA 8 Cross Section 13 Annual Plots



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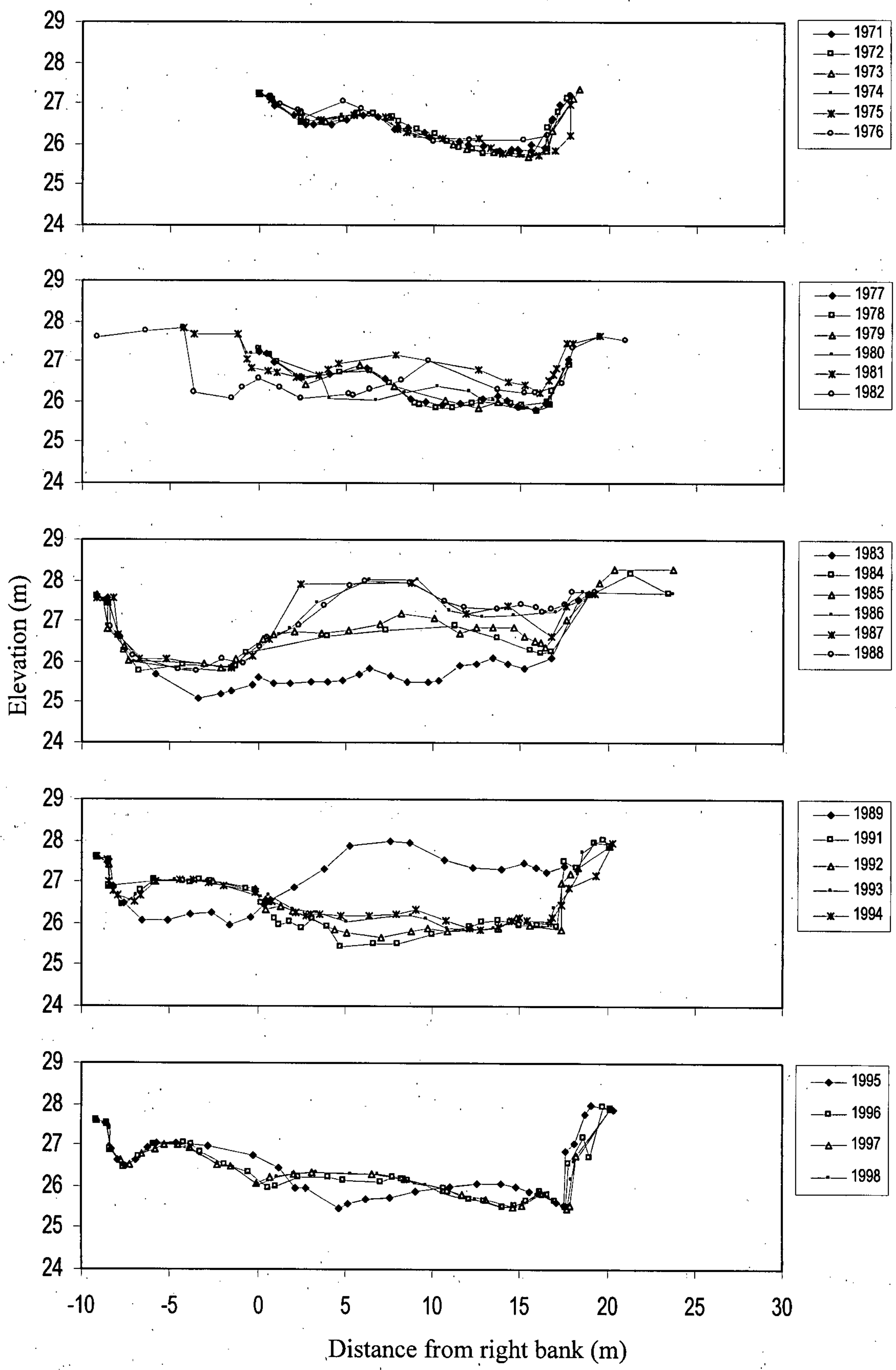

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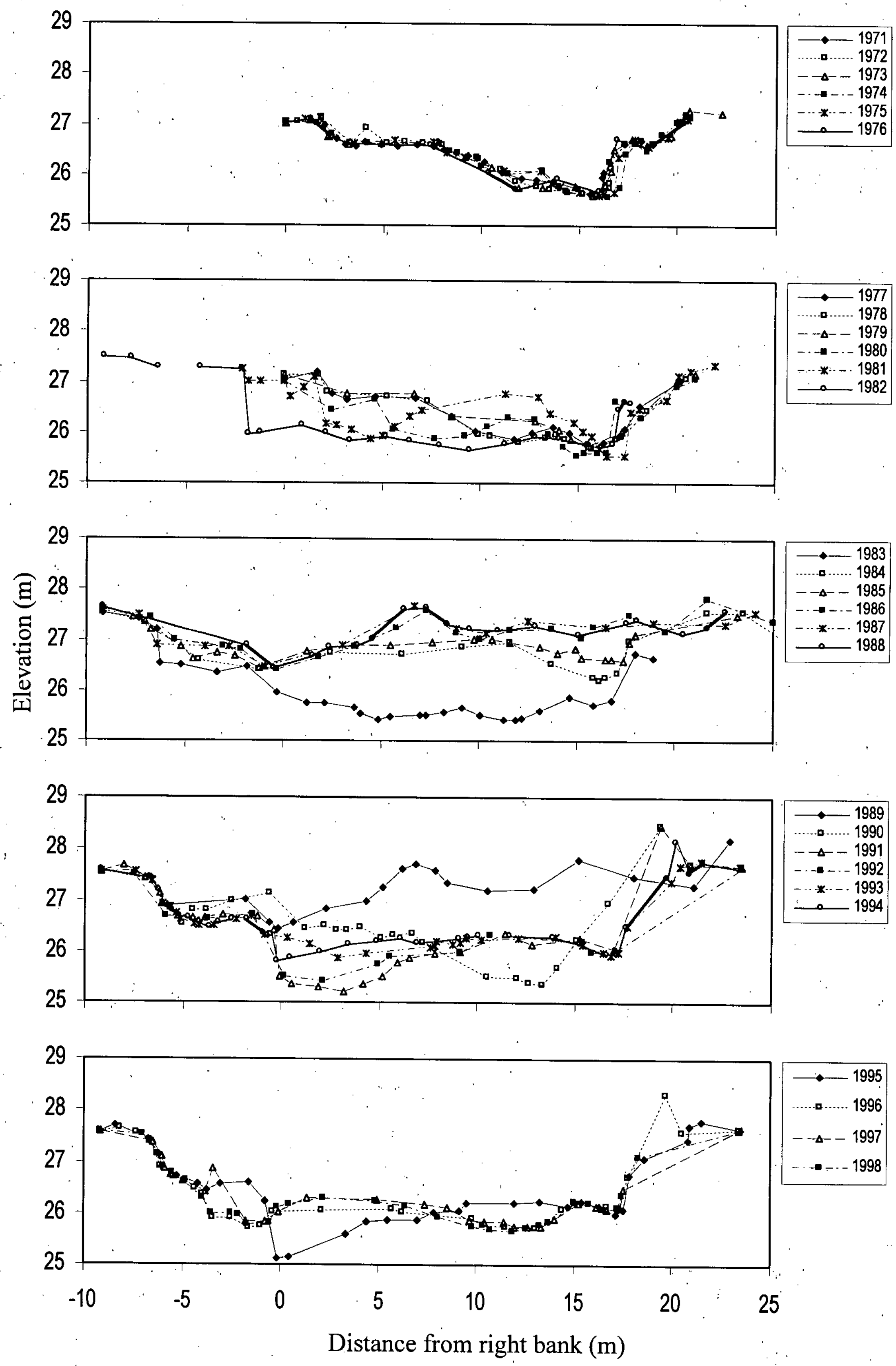
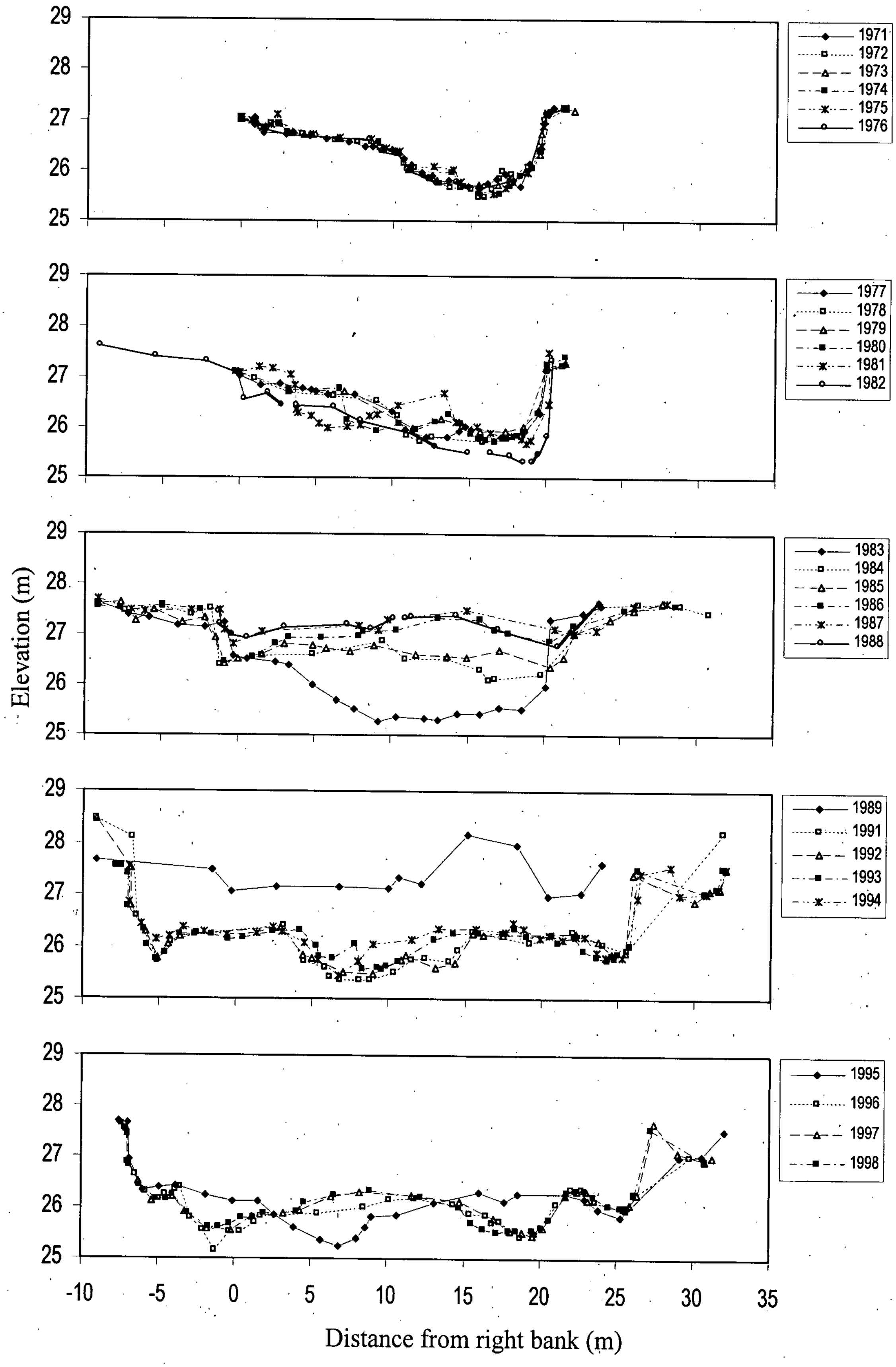


SA 8 Cross Section 16 Annual Plots



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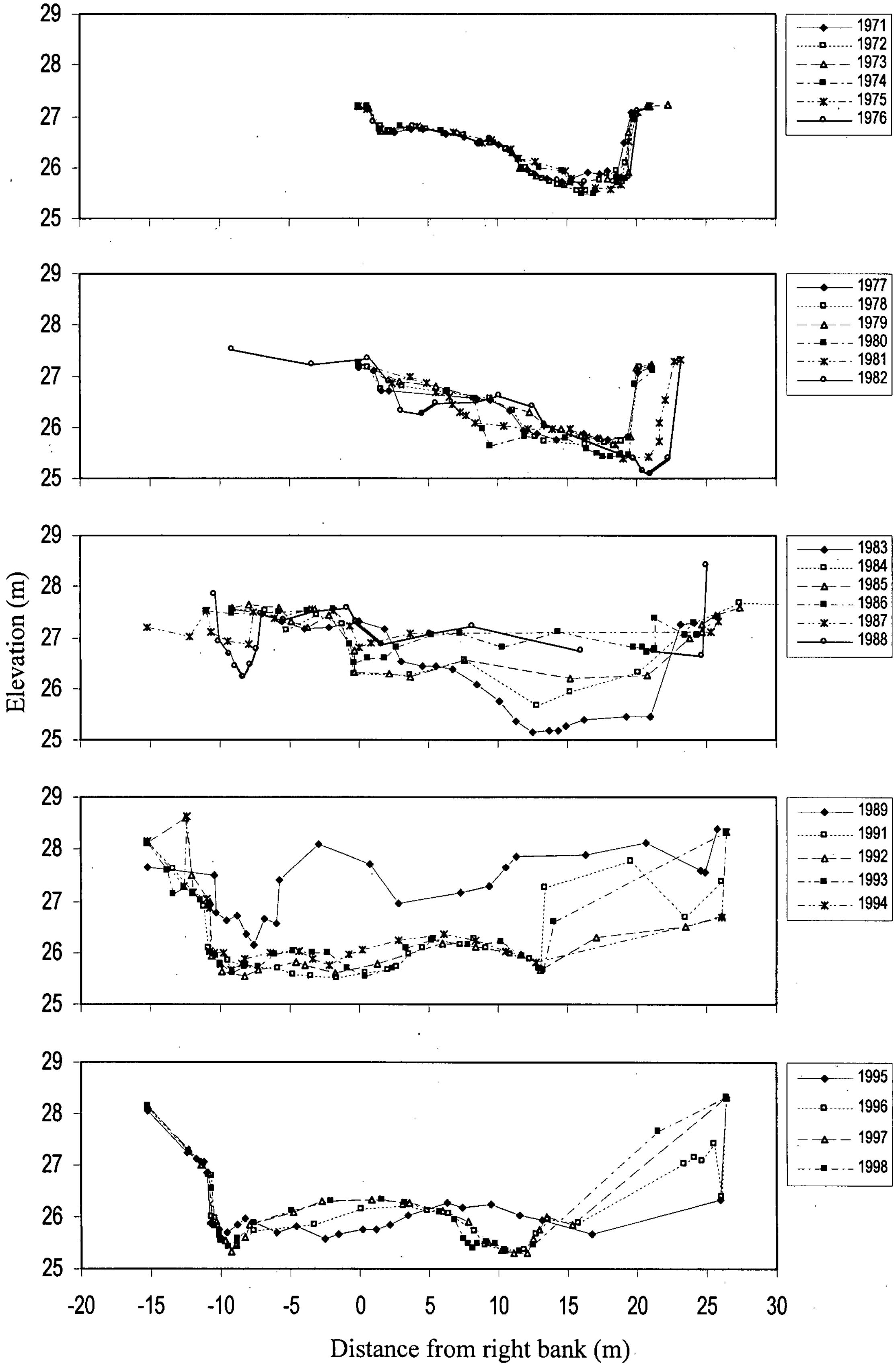

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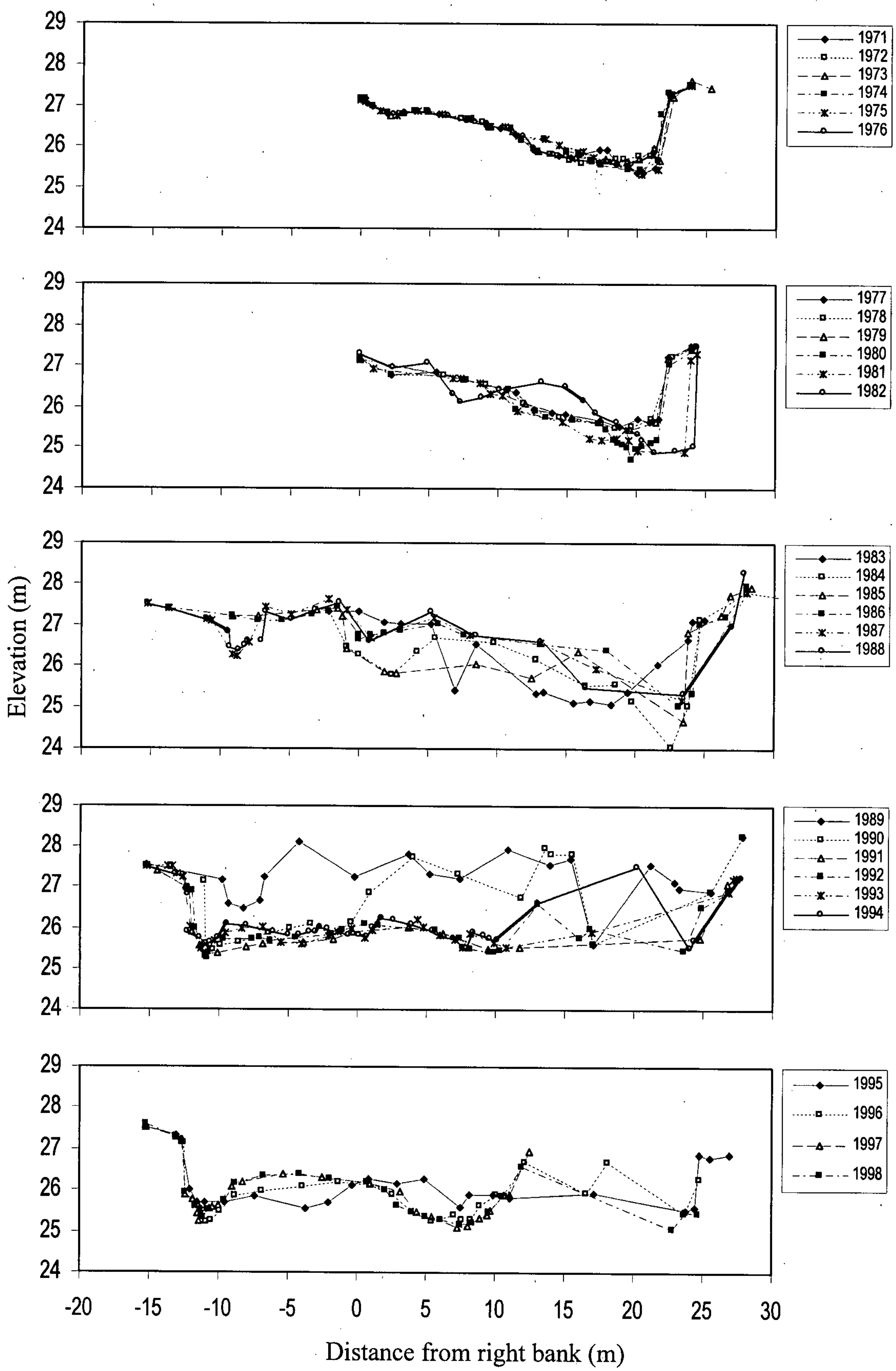
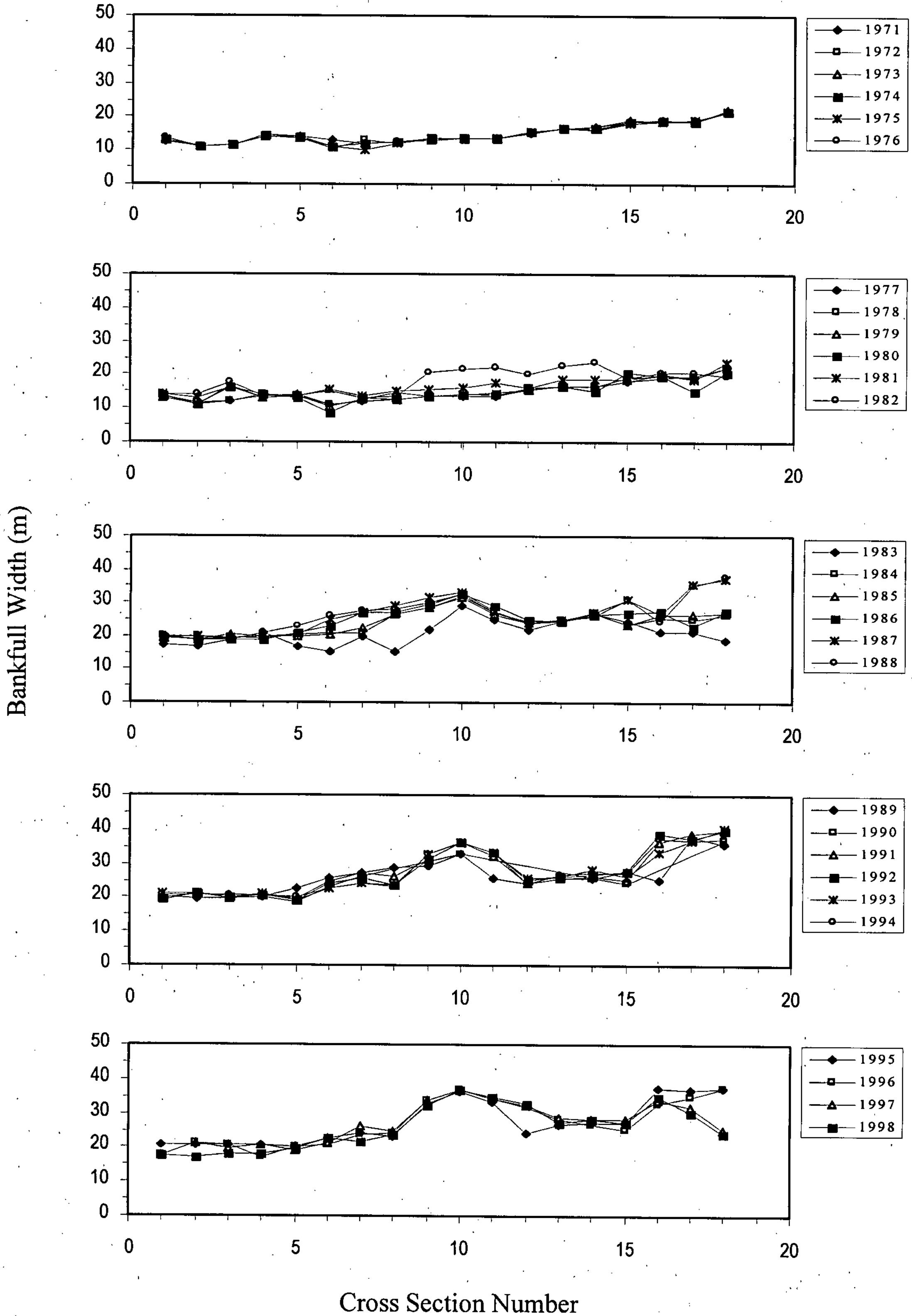


SA 8 Annual Bankfull Widths



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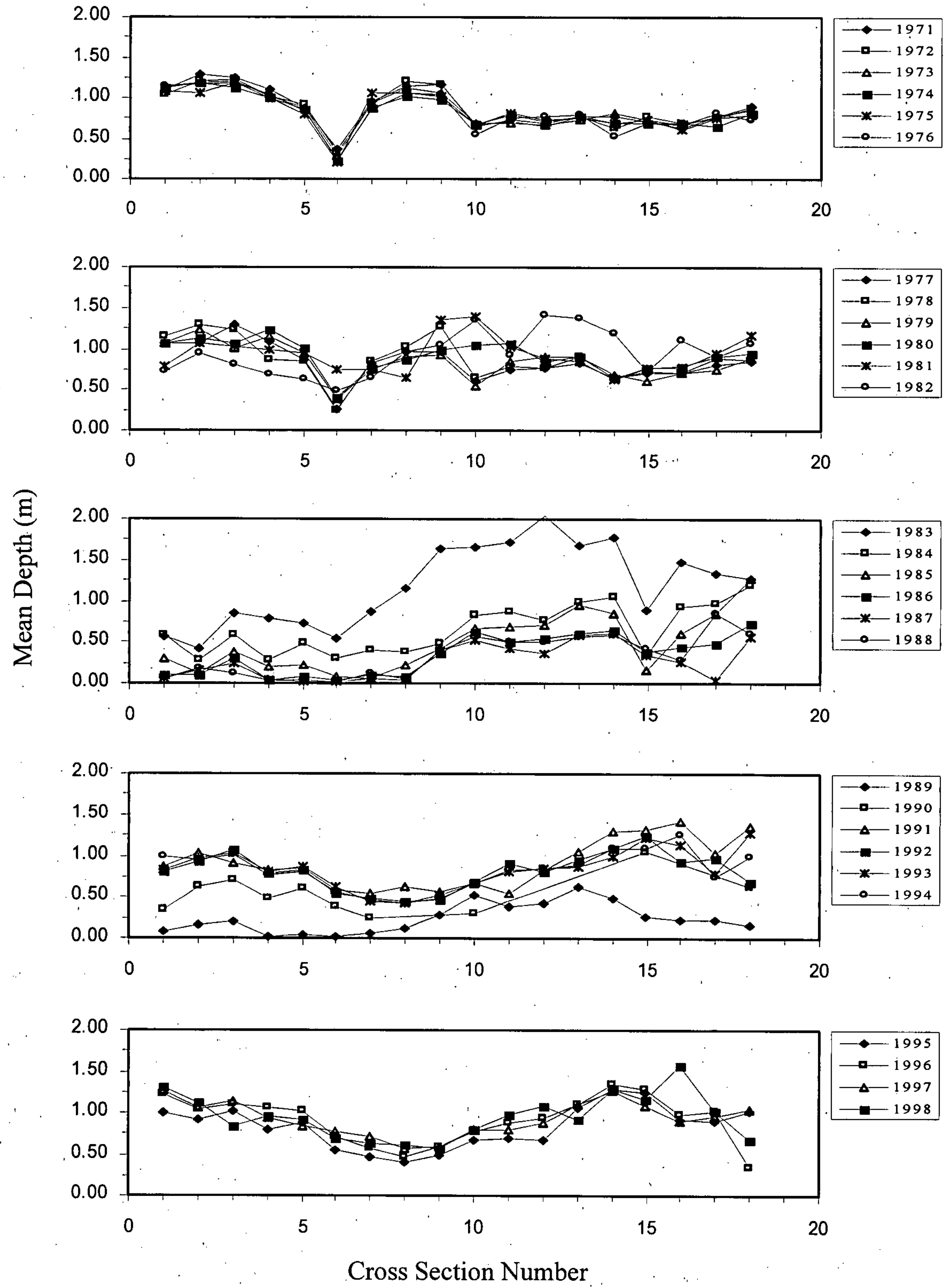

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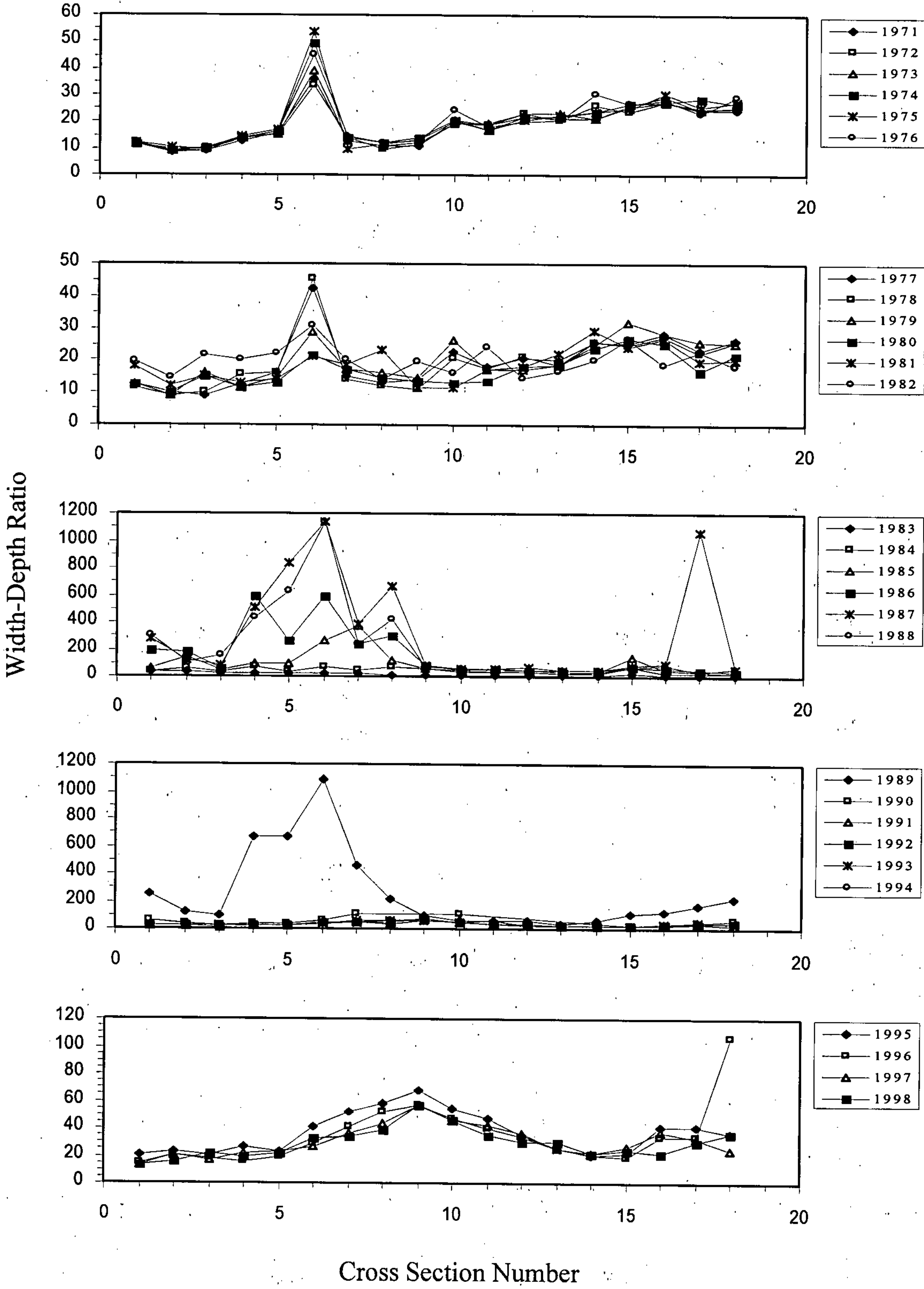
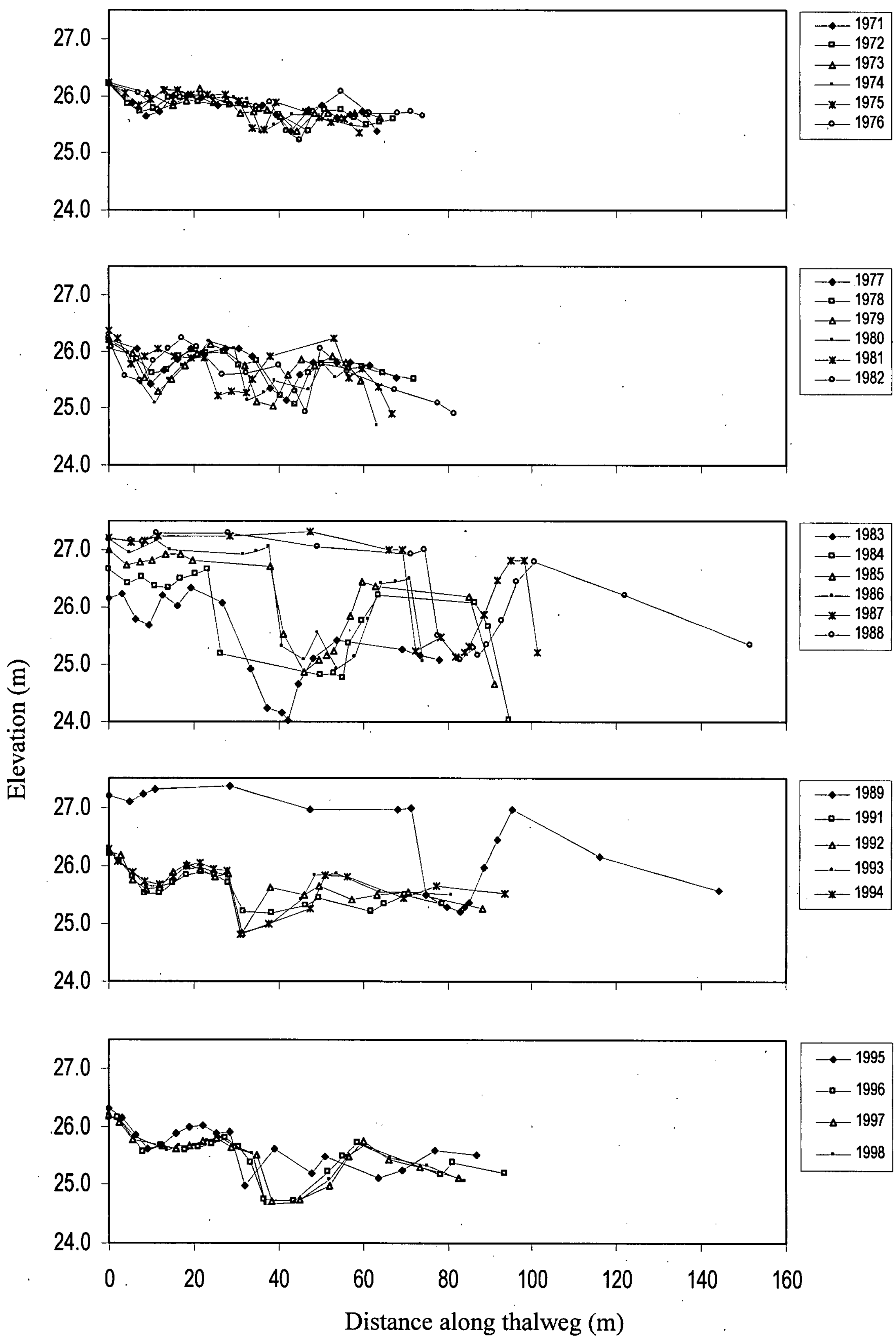
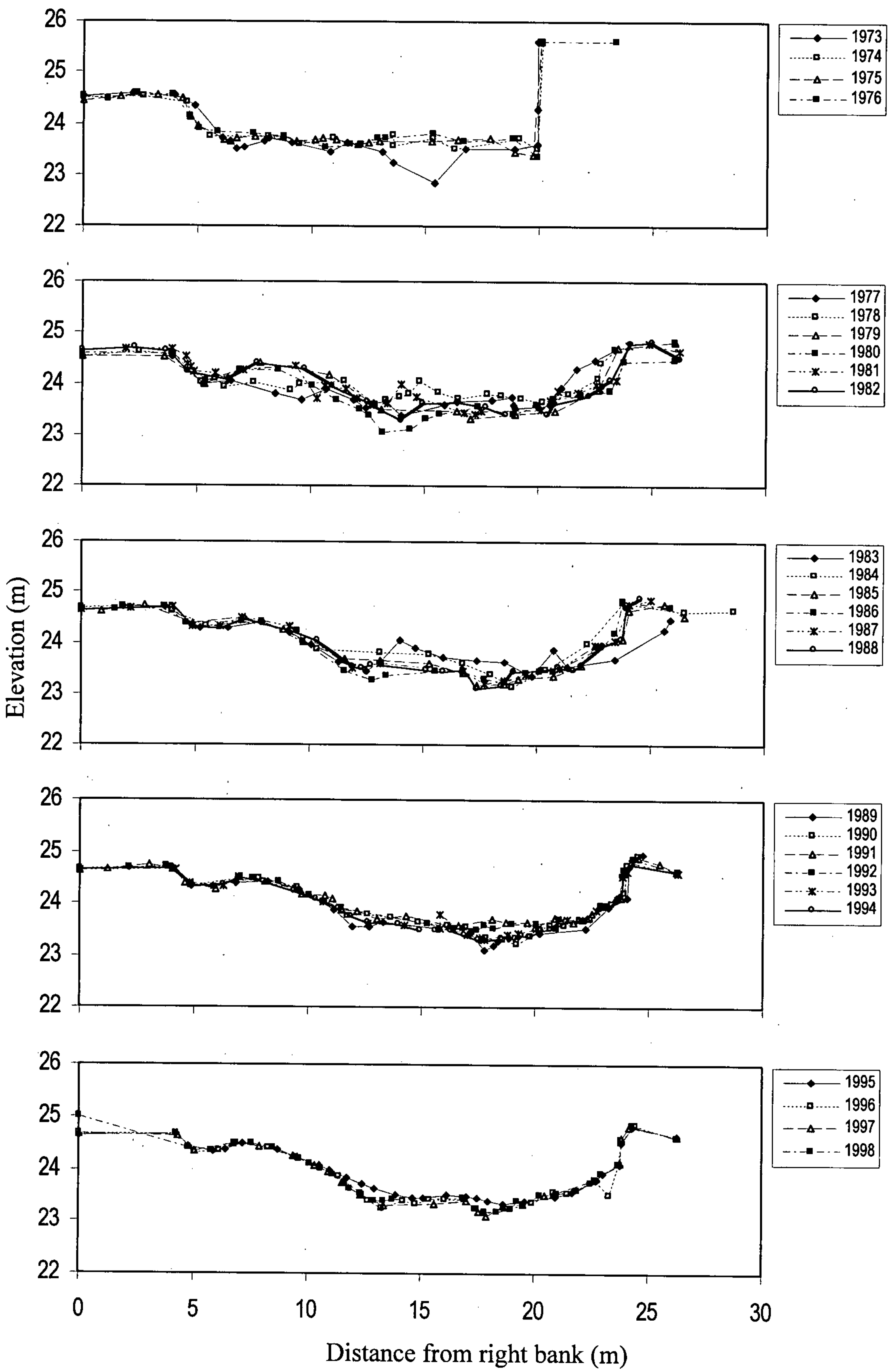


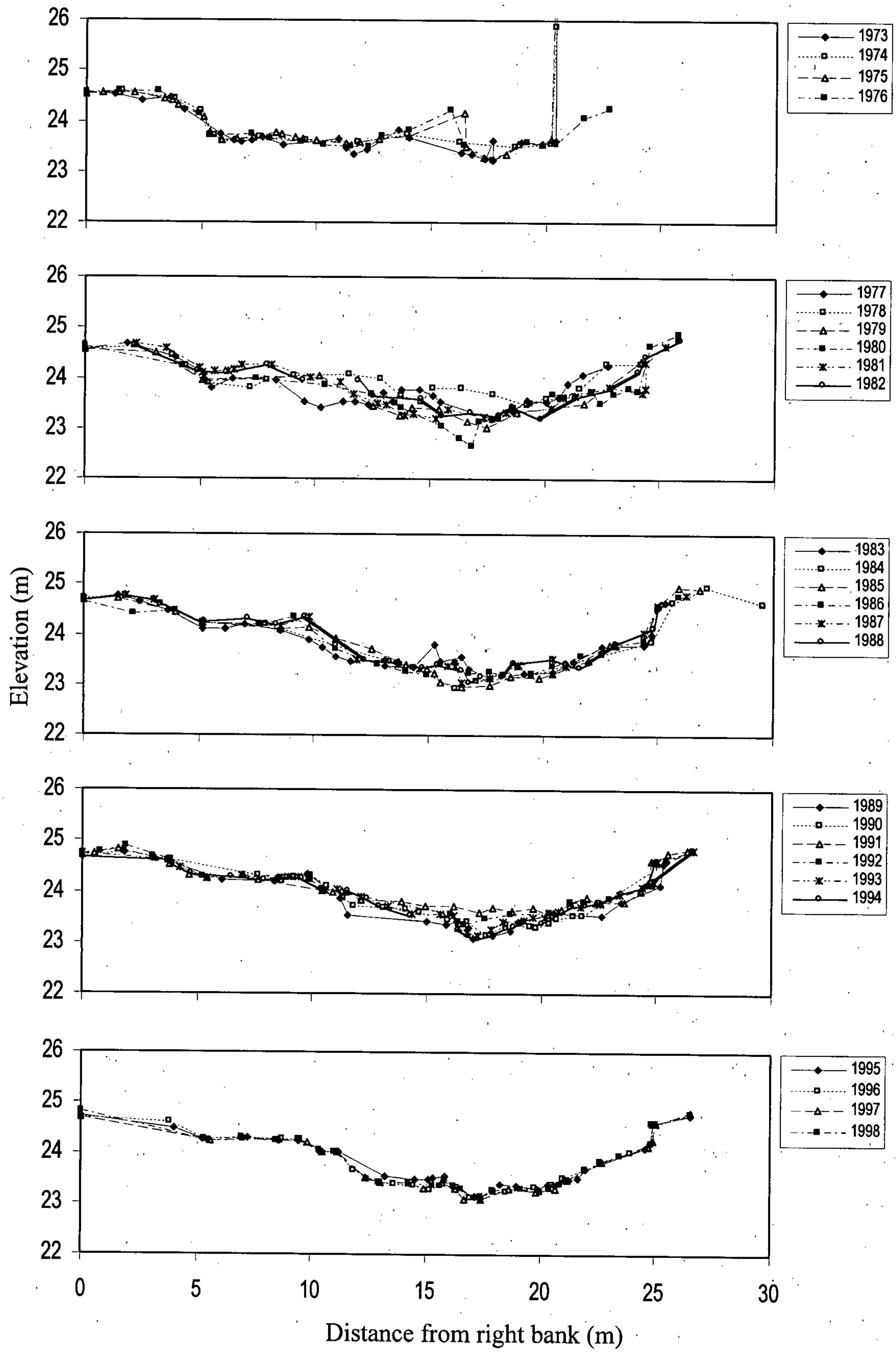
SA 8 Annual Longitudinal Profiles



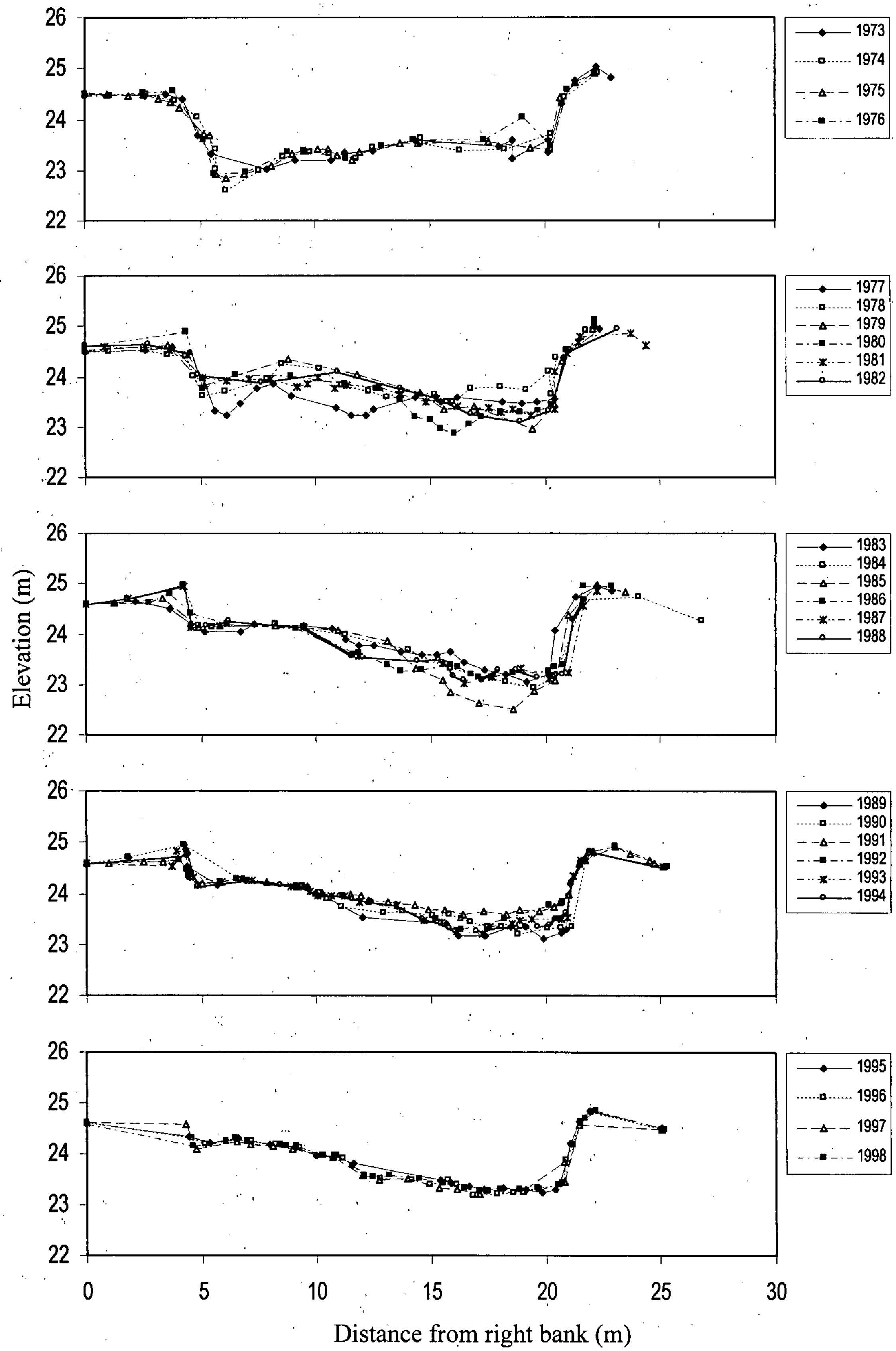
SA 7 Cross Section 1 Annual Plots



SA 7 Cross Section 2 Annual Plots



SA 7 Cross Section 3 Annual Plots



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