AN ABSTRACT OF THE THESIS OF

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Title: Storage Dynamics of Fine Woody Debris For Two Low-order Coastal Streams In Southeast Alaska.

Abstract Approved: Redacted for Privacy Robert L. Beschta

The characteristics and associated storage dynamics of approximately 2000 pieces of fine woody debris (FWD; 2.5 cm <diameter<10 cm and 0.3 m<length<10 m) was evaluated over a three-year period in two undisturbed salmonid nursery streams in Southeast Alaska. To index a given reaches propensity to capture and store FWD over time, 100 survey stakes (diameter=2.9 cm, length=44 cm) were introduced at one-year intervals to the head of four reaches with distinct coarse woody debris (CWD; diameter>10 cm, length>1 m) loadings, and their downstream dispersal monitored.

Between 1987 and 1989, storage of FWD was temporally and spatially variable and not suggestive of steady-state conditions. In the 1987-1988 stormflow period, the total resident FWD volume (cm^3 per meter of reach) declined 43%. This was followed by a resident volume increase of 9% in the 1988-1989 period. These changes in FWD storage occurred despite maximum peak flows which differed between

periods by only 10%. These annual changes in FWD storage indicate that factors and processes in addition to magnitude of peak flow were important in FWD storage dynamics. Factors important in describing the observed storage fluctuations might include the effects of an unusually low peak flow regime (20% of nine-year average) in the year prior to the study's commencement, as well as variable rates of FWD recruitment from the riparian environment.

The majority of FWD was shorter (66-102 cm) than bankfull width (3.8-5.6 m), approximately 4.7 cm in diameter, geometrically simple in form, and in moderate to advanced states of decay. Shorter pieces were generally entrained more frequently than longer pieces, resulting in selective retention of longer pieces through time. The data strongly suggest FWD loadings are positively correlated with the amount of CWD in the reach.

Retention of stakes was generally highest in a reach with high CWD loading (0.47 m^3/m), intermediate in two reaches with moderate CWD loading (0.13 m^3/m and 0.11 m^3/m), and lowest in a reach with low CWD loading (0.0082 m^3/m). Distinct spatial and temporal stake dispersal patterns were noted between reaches. The retention of stakes declined most dramatically during the first stormflow (1.31 m^3/s) following their introduction, while succeeding storms of equal or greater magnitude had less of an effect.

Storage Dynamics of Fine Woody Debris For Two Low-order Streams In Southeast Alaska

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX TABLES

STORAGE DYNAMICS OF FINE WOODY DEBRIS FOR TWO LOW-ORDER COASTAL STREAMS IN SOUTHEAST ALASKA

INTRODUCTION

In recent decades, research concerning the nature and role of woody debris in forested stream ecosystems of the Pacific Northwest (Harmon et al. 1986, Bisson et al. 1987), has largely indicated that woody debris is an important factor influencing fish habitat (Sullivan et al. 1987), sediment routing (Lisle 1986), stream biology (Triska and Sedell 1975), and channel morphology (Keller and Swanson 1979, Robison and Beschta 1989). These studies have generally focused on either coarse (>10 cm in diameter) or particulate (twigs, cones, and branches <2 cm in diameter) woody debris. Between these two size categories lies a range of woody debris pieces that have been relatively unstudied and may have implications within the stream environment similar to, interactive with, or different from the above.

The purpose of this research is to evaluate the physical characteristics, distribution, and storage changes of fine woody debris in undisturbed, low order, streams of coastal Southeast Alaska. Specific objectives include:

1) Quantify and identify factors affecting storage of fine woody debris in low gradient, first- and second-order streams over time.

2) Asssess the role of coarse woody debris loadings and flow regimes upon the transport and storage of fine woody debris.

3) Evaluate transport distances and characterize "trap" sites associated with introduced fine woody debris of uniform dimensions.

Quantification of fine woody debris (FWD) storage through time provides a basis for evaluating the hypothesis that FWD inputs and outputs in a given reach are non-uniform and are temporally dependent upon both chronic and episodic natural phenomenon. These phenomenon include, for example, weather related recruitment of debris from the riparian forest and stream hydrograph fluctuations. Such information could also provide baseline data on the variability of FWD storage possible in low-order streams. Extrapolation of recruitment and transport processes to other similar coastal stream areas may be possible.

The degree to which coarse woody debris (CWD) loadings are associated with the storage of FWD will determine the validity of the hypothesis that stream reaches with higher CWD loadings retain FWD at greater levels than those with lesser loadings. Retention may be linked to CWD's capacity to trap and store FWD and enhance the formation of small debris dams. Information gained could be useful within the context of organic budgets in ecological studies as well as have implications for CWD management.

The introduction of FWD of uniform dimensions to a stream and its dispersion along the channel may index a stream's propensity to store or export naturally occurring FWD under various flow regimes. Additional information will be gained regarding physical features within the channel that are associated with the trapping of mobile woody debris.

BACKGROUND

Fine woody debris is often referred to as "slash", small woody debris, sticks and branches (<10 cm in diameter), and small mobile debris. These references are most often found in literature pertaining to CWD in stream channels, and are seldom quantified. Detailed debris loading studies (Froelich 1973, Swanson et. al. 1984, Duncan and Brusven 1985), have been conducted which compared and contrasted woody debris loadings in logged and unlogged stream channels. These studies quantified in-channel FWD loads at a point in time, but did not evaluate year-to-year changes in volume and distribution.

Because there is no single accepted FWD classification scheme in the literature, it is difficult to draw inferences between small woody debris loadings which are reported in ecologically and geographically distinct basins. The frequency of observations concerning small woody debris in ecological, morphological, and hydrological stream studies suggests the need for a more detailed classification system for FWD in forested stream environments.

WOODY DEBRIS BUDGETS

Organic matter budgets in natural streams are often looked upon in absolute terms, with an implied assumption that the inventoried stream's budget reflects a steady state condition. An alternate assumption is that organic matter loading (measured as some volumetric or mass element per channel area or length), is temporally and spatially dynamic, changing over time in response to a host of chronic and episodic natural phenomeon (Cummins et. al. 1983).

Phenomenon important in altering woody debris budgets over time in a given reach have the ability to either add, stabilize, or export debris. Inputs of woody debris into the stream channel can be affected by chronic events such as natural tree mortality, windthrow and bank undercutting, or episodic events such as major blowdowns, mass soil movements and debris avalanches (Keller and Swanson 1979). Any of these events may influence local channel conditions for an extended period of time.

Infrequent and large flow events can similarly have profound effects upon the temporal and spatial rate of recruitment, storage, and export of organic matter (Cummins et. al. 1983). Recruitment processes include entrainment of floodplain debris and accelerated bank undercutting. Storage can be increased by importation of debris from upstream which becomes trapped at a stable location by high flows, or reduced at a site by mobilization and transport of resident debris. A net export at an upstream site may result in a net import to another site downstream.

It is desirable to generate woody debris budgets within the context of historical natural regimes. A consideration in the generation of these budgets is the relationship between any one segement of stream to processes taking place up- and downstream. This perspective is embodied in the Stream Continuum Theory (Vannote et. al. 1980), which recognizes linkages in biotic and physical processes between spatially distinct segments along a stream's length. Although the quantification of all linkages and relationships is not currently possible, awareness of this theoretical model should be useful in woody debris analysis.

Fine Woody Debris Inputs

FWD can enter the stream channel as a consequence of whole tree recruitment and subsequent breakage into smaller pieces or singly as branches. As with CWD recruitment, FWD inputs are related to the characteristics and spatial distribution of the riparian forest and the occurrence of natural phenomena that work upon it.

Specifically, FWD arrives at a given reach through :

a) Flotation from upstream

Parameters surrounding this 'input' process are assumed to be similar to those described for CWD, including stream discharge and the size and length of individual pieces (Keller and Swanson 1979). To be transported downstream, pieces must first be entrained. Factors involved with entrainment at varying discharges are likely to be complex, though a function of individual piece stability, position in channel, piece morphology, and the presence or absence of structural elements in the channel which may act to constrain or enhance movement.

b) Weather related processes

Inputs of branches and treetops are common in old growth riparian zones which are prone to high winds or heavy snowfall (Bisson et. al. 1983). Sidle (1985) reported that woody material inputs along Bambi Creek, a second-order Southeast Alaska coastal stream, were most significant in winter and spring seasons, suggesting the importance of wind, ice and snow as factors in debris recruitment from the riparian forest. Relative to riparian forests in Oregon, which are often dominated by Douglas Fir (Psuedotsuga menziesii), Alaskan conifers are more densley limbed (Swanson et.al. 1984), making them a significant potential source of FWD. Swanson et. al. (1984) suggested that this may account for the higher proportions of woody debris found in Southeast Alaskan streams.

c) Breakage from whole trees

Though not quantified in the literature, it is assumed that the processes responsible for CWD recruitment also result in significant inputs of FWD into the stream channel. Conversion of CWD to FWD can occur through breakage on impact during whole tree recruitment, battering by hydraulic forces, and eventual decomposition and disintigration.

d) Logging inputs

Instream FWD accumulations in SE Alaska are much greater in logged than in unlogged basins (Swanson and Lienkaemper 1978, Swanson et. al. 1984, Duncan and Brusven 1985). The increase in accumulation has been observed to be up to 6 times greater in logged basins 6-10 years after harvesting (Swanson et. al. 1984).

Fine Woody Debris Outputs

Once in the channel, FWD may leave a site by the following mechanisms:

a) Flotation downstream

FWD may be relatively easy for low order streams to transport during typical runoff events. This is in contrast to CWD, which usually remains where it fell in the channel because runoff is seldom of sufficient magnitude to redistribute it (Swanson and Lienkaemper 1978). The magnitude of given runoff events may affect the entrainment and subsequent transport of FWD.

b) Decay

The rate of decay of woody debris varies, with hardwoods (deciduous species) decaying faster than softwoods (conifers). Decay rates are also dependent upon whether the individual piece is submerged, partially submerged, or terrestrial (Triska and Cromak 1980), due to the different habitat requirements of the microbes and macroinvertebrates responsible for its breakdown. Biologic and mechanical breakdown by stream components can convert whole pieces into particulate organic matter which may be more easily exported from a site.

c) Debris cleanout after logging

The extent to which FWD is removed from streams during or after harvesting is seldom quantified in the literature. The amount of cleanup will vary from location-to-location based upon regional harvest management activities.

Fine Woody Debris Retention

The retention of organic material in streams refers to the amount of time introduced organic material is retained at a given point. This includes the immediate trapping of organic material and its long- or short-term storage at a site (Speaker et.al. 1984). Duration of storage can have implications for the biotic components of a stream and will be discussed later.

There are several factors which may affect the retention of FWD in the stream channel:

a) Runoff regime

Infrequent and large flow events may significantly alter the volume of material trapped, stored, or transported from a site. Conversley, periods with below "normal" runoff could prolong retention times for individual pieces which require large flows for entrainment.

b) Trap sites

Within the stream channel are numerous structural features that are capable of trapping and storing FWD. These may be of fluvial origin, as in the case of mobile bed material and undercut banks, geomorphic (channel meanders and constrictions), geologic (bedrock intrusions or boulders), or organic (debris dams, individual pieces of CWD, overhanging vegetation). These structures may also interact with each other within the channel and function differently as trapping agents at varying flow levels.

c) FWD stability

The relative stability of FWD over a period of time may be related to the type of trapping agent. For example, a piece of FWD which was trapped against a single piece of CWD by stream currents may not be as stable as a similar piece trapped within a debris dam. .Even within the debris dam, FWD pieces may become more or less stable over time as high flows add or dislodge pieces. Bedload movement may also play a role in stability as mobile material either buries debris during deposition or uncovers it during scour.

d) Individual piece morphology

Although FWD is generally considered to be mobile, individual pieces are often bent, crooked, branched and rough textured. It is possible that highly irregular pieces will have a greater propensity to be trapped, snagged or attached to existing channel roughness elements. If these pieces become more simple in form due to abrasion, weathering or decay, they may become more easily transported, with less liklihood of being trapped.

Debris Dams and FWD Storage

In stream systems where coarse woody debris is a dominant roughness element, the occurrence of debris dams may be augmented by FWD. Studies of logged basins in Southeast Alaska suggest that stable pieces of CWD can act as sieves for smaller floatable debris, enhancing formation of debris dams (Bryant 1980). In low-order streams, mass blowdowns have been reported to trap FWD in this manner and thus initiate dam formation (Swanson et. al. 1976, Bryant 1983). Small debris trapped against single fallen trees has been observed to promote local scour which obscured fluvial created pool-riffle sequences (Estep and Beschta 1985). Debris dams and accumulations have the potential to affect channel morphology by diverting flow and trapping sediment (Swanson et. al. 1976), create pools important for fish habitat (Bryant 1983), and provide provide storage sites for biological detritus and products of metabolic breakdown (Bilby and Likens 1981). For these reasons, relationships between FWD and CWD should be of interest in low-order streams.

BIOLOGICAL ROLE OF FWD

Allochthonous inputs of organic debris from riparian forests have an important function in the energetics and structure of lotic ecosystems (Hynes 1975, Vannote et. al. 1980, Cummins et. al. 1983). Up to 70% of all allochthonous inputs in coniferous forested streams occurrs as woody debris of varying sizes (Triska et. al. 1984).

Woody debris is thought to have two main ecological functions: the physical retention of finer organic debris and as a refractory carbon source broken down abiotically by water movement and biotically by microbes and macroinvertebrates (Triska et. al. 1982, Bisson et. al. 1983). Without retention, organic matter cannot serve as a nutritional resource for aquatic biota (Gregory et. al. 1987). FWD has been linked, through its structural role in debris dams, with a streams ability to store detritus and organics in sediment, which are important carbon sources (Bilby 1981).

Research conducted in a low-order Oregon stream (Speaker et. al. 1984), found that debris less than 10 cm in diameter greatly enhanced the potential for leaf retention in streams. This trapping was observed in conjunction with debris dams and individually with discreet pieces of FWD within the channel. Leaves are considered to be a high quality food source for macroinvertebrates.

Woody debris is largely refractile and is not considered a primary food source for macroinvertebrates (Anderson and Wallace 1984). However, evidence suggests woody debris provides important substrate for microbes which are important food sources for aquatic insects (Anderson and Sedell 1979). Microbial decay of wood is in part a function of the surface-to-volume ratios of woody debris (Bisson et. al. 1983), with higher ratios considered the most favorable. Compared to CWD, the surface-to-volume ratio of FWD is high, making it conceivable that FWD is an important microbial substrate (Triska and Cromack 1980). For example, a piece of CWD with dimensions 4000 cm in length (L) x 20 cm in diameter (D) has a surface to volume ratio of 0.2:1, while a piece of FWD with dimensions 25% as large, 1000 cm (L) x 5 cm (D), has a ratio of 0.8:1.

Fine woody debris accumulations may also be a factor influencing fish habitat. McMahon and Hartman (1989), observing habitat utilization of juvenile coho salmon, found preferential utilization by the salmon of an introduced accumulation of branches 3-6 cm in diameter. They concluded that the channel complexity created by the accumulation provided favorable cover, shading, and velocity refuge.

FWD MANAGEMENT

Swanson et. al. (1984) have suggested that the alteration of instream debris loads be undertaken conservatively, by first gaining an understanding of debris conditions typical of undisturbed streams. Manipulation of instream debris loads has largely focused upon CWD. Furthermore, the managment of CWD has come full circle; from widespread removal of CWD to facilitate fish passage (Meahan et. al. 1969) to the introduction of woody debris to "enhance" habitat (Bisson et. al. 1987). Because FWD volume is often found at increased levels following harvesting, and its potential role in creating channel structure in association with CWD, it may warrant consideration when debris management plans are generated.

Bryant (1983) suggested the removal of all loose woody debris <10 cm in diameter from the stream channel following harvesting operations near salmonid nursery streams. However, he also indicates that woody material in this size range may be flushed from the system within 5 years of its introduction. Bryant's (1983) recomendation and speculation highlights the uncertainty a mananger may face when contemplating alteration of FWD loads. Until more is known about the storage and movement of FWD in small streams, these uncertainties will remain.

An additional consideration in the mangagement of FWD relates to its potential to compromise forest road drainage structures. Small floatable debris may be a factor in reducing the capacity of culverts at stream crossings (Piehl et. al. 1988), which may in turn lead to culvert damage or failure during large storm events (Swanson et. al. 1984). Knowledge of FWD debris loads and the flows required to entrain them may be useful in assessment of drainage structures.

METHODS

LOCATION AND CHARACTERIZATION OF STUDY SITES

The two streams evaluated in this study, Bambi and Beach Creeks, are located on Chichagof Island in Southeast Alaska, approximately 100 km south-southwest of Juneau (Figure 1, Appendix A). Both flow into Trap Creek, a third order stream which empties into Tenakee Inlet. Both Bambi and Beach Creek experience tidal influences in their lower reaches.

The area recieves approximately 170 cm of rain a year (Sidle 1988), of which 15% falls in October, the wettest month (Water Resources Atlas for Alaska 1978). Approximately 40% of the yearly precipitation occurs from September through November (Sidle 1988). Most of the precipitation occurs as steady light to moderate rain at sea level with snowfall increasingly important at higher elevations (Estep 1984).

The Trap Bay basin is a glacial cirque valley bounded by serrated ridges and a horn peak at the southern end (Estep 1984). Elevation of the watershed ranges from just above sea level to approximately 1320 meters. Bambi and Beach Creek originate on ridgetop muskegs, flow over steep headwalls (>50% slope), into valley bottoms with <3% slope (Bryant 1984, Robison 1988).

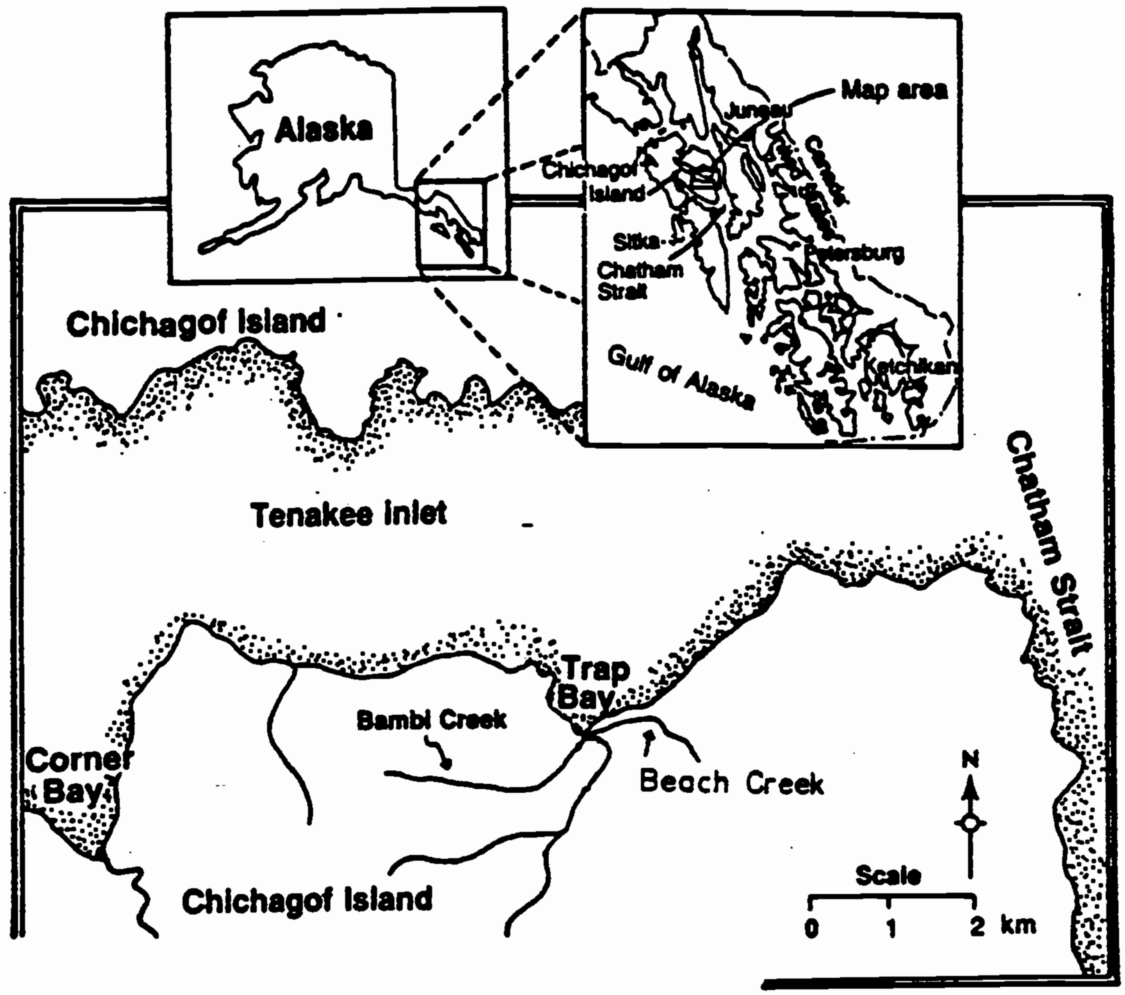


Figure 1. Location of study streams (After Sidle 1988)

Vegetation along the streams consists of an overstory of red alder (Alnus rubra), and old growth Sitka spruce (Picea stichensis) and Western hemlock (Tsuga heterophylla) (Table 1). The understory is often dense and dominated by devils club (Opoloponax horridum), with skunk cabbage (Lystichum americanum), salmonberry (Rubus spectabilis) and huckle- and blueberry (Vaccinium spp.). The lower 110 m of Bambi Creek and 100 m of Beach Creek flow through open reaches with streambank vegetation dominated by beach grasses.

Coarse woody debris distribution and volume on both creeks have been reported by Robison (1988) and Robison and Beschta (1989). Debris accumulations range from mostly absent in the tidal influence zones to heavy in blowdown areas (Table 2). As part of a fisheries experiment, an 88 m section of Bambi Creek (beginning 377 m upstream from Bambi Creek's confluence with Trap Creek) was cleaned of all instream CWD.

Coho (Oncorhynus kisutch), pink salmon (Oncorhynus gorbuscha) and Dolly Varden char (Savelinus malma) are present in both streams. Though all species have been observed to inhabit 1000 m of Beach Creek and 1500 m of Bambi Creek, the lower 300 m of both are the most heavily utilized (Bryant 1984). Beaver (Castor canadensis), Sitka blacktail deer (Odocoileus hemionus), and brown bear (Ursus americanus) are also active in the basin.

Table 1. Riparian vegetation, substrate type, and channel bank morphology associated with study streams (After Bryant 1984).

Distance From Confluence (m)	Riparian Vegetation	Substrate	Banks
Bambi Creek			
0-100	Grass/alder	Pea size angular gravel	Undercut with opposing gravel bars
100-500	Spruce/hemlock	Fine gravel	Root stabilized undercut banks
Beach Creek			
0-100	Alder/grass	Fine gravel	Sod, root stabilized, shallow side slopes
100-200	Beach fringe spruce/hemlock	Fine to pea size gravel	Cut-banks, gravel bars, undercuts with root tangles
200-600	Spruce/hemlock	Fine to pea size gravel and organics	Root bound soil, organics, undercuts

Table 2. Reach locations on Bambi and Beach Creeks with length, riparian stand density, CWD load, and selected channel morphology characteristics of each (Adapted from Robison 1988).

Characteristic	Bambi Creek		Beach Creek		
	Intertidal	Main	CWD-1	CWD-2	CWD-3
Distance from confluence (m)	0-165	166-506	394-441	531-580	626-663
Length (m)	165	341	47	49	36
Riparian stand *					
Number of conifers /m stream **	-	-	1.8	1.2	3.0
Median diam. (cm)	-	-	21.0	20.0	12.0
CWD load					
Total vol. (m^3)	0	235	1.2	61.2	29.6
Vol. zone 1+2 (cm^3/m)	0	106,000	8,200	125,000	474,000
Vol. zone 3+4 (cm^3/m)	0	585,000	18,300	1,119,000	337,400
Channel morphology					
Average low-flow depth (cm)	20	15	13	27	28
Average slope (%)	1.1	1.5	1.0	2.2	1.6
Average bankfull width (m)	3.9	4.4	4.8	3.8	5.6

* Conifers within 30 m of channel
** Number of riparian conifers/reach length

Bambi and Beach Creeks are second- and first-order tributaries to Trap Creek, respectively. Bedrock and boulders are largely absent from the study reaches, with a bed substrate that consists mainly of cobbles and gravel (Table 1). Average stream width, bankfull width, and low flow thalweg depth and gradient in reaches of interest are given in Table 2.

A mean annual peak flow for Bambi Creek of 1.56 m^3/s was estimated from 9 years of discharge data from a recording stage gage located approximately 400 meters upstream of its confluence with Trap Creek. The gage was non-operative from approximately late November to mid-March for all years of record. Because most large storms in the basin have been reported to occur in the autumn months (Sidle 1988), the autumn high flows were considered to be approximate annual high flow regimes. Average summer low flow was estimated by Robison (1988) to be 0.04 m^3/s.

Discharge records were not available for Beach Creek. A mean annual peak flow of 0.75 m^3/s was estimated by weighting Bambi Creek flows by the ratio of the two drainage areas (area Beach Creek:area Bambi Creek). The weighted area ratio was 0.48.

The Trap Bay basin is essentially undisturbed (no significant changes to the watershed due to human influence) and has been the site of extensive and varied research for several years. Suspended sediment and bedload studies on Bambi Creek have been reported by Sidle and Campbell (1985), Campbell and Sidle (1985) and Sidle (1988). Fish populations on both creeks have been reported by Bryant (1984) and further studies are currently ongoing. Riparian vegetation has been characterized by Alaback and Sidle (1986); CWD and channel morphology by Robison (1988) and Robison and Beschta (1989). Mass movement studies in the Bambi Creek watershed have been reported by Sidle and Swanston (1982).

FIELD METHODS

Designation of Study Reaches

Bambi Creek FWD loadings were evaluated for 506 m upstream (measured along the thalweg) of its confluence with Trap Creek. The upstream endpoint was chosen to coincide with the end of previously established fisheries study reaches. Also, above this point the stream characteristics began to differ more dramatically from the lower 500 m in terms of overall channel morphology and CWD debris loads (Campbell and Sidle 1985). For some analysis, the entire reach was subdivided into an Intertidal, Central, Cleaned, and Upper reach (Appendix Table 1).

The Beach Creek study reach also began at its junction with Trap Creek and continued upstream for 663 m. This reach was further subdivided into 3 sections. Three sections with distinct CWD loadings, (CWD-1 with a low CWD load, CWD-2 with a moderate CWD load, and CWD-3 with a high CWD load; Appendix A and Table 2) were identified above the tidal influence zone. Coarse woody debris loads and channel morphology values are from Robison (1988).

FWD Surveys

Five FWD load surveys were made between the fall of 1987 and the summer of 1989. The first three surveys were designed to quantify and characterize the storage of FWD in the study streams following individual storm generated runoff events. The first survey consisted of an inventory which located and characterized all FWD; two subsequent surveys monitored individual piece movement resulting from fall and winter storms. The fourth and fifth surveys were conducted during July of 1988 and 1989, respectively. These surveys measured: (1) the location of previously identified FWD, (2) identified, located, and characterized new FWD that had entered the system over the winter/spring and (3) recharacterized piece morphology.

Concurrent with the first and fourth surveys, 100 color-coded survey stakes of uniform dimension (2 cm x 3.8 cm x 44 cm) were introduced at the head of the CWD-1, CWD-2 and CWD-3 reaches on Beach Creek and also at the head of

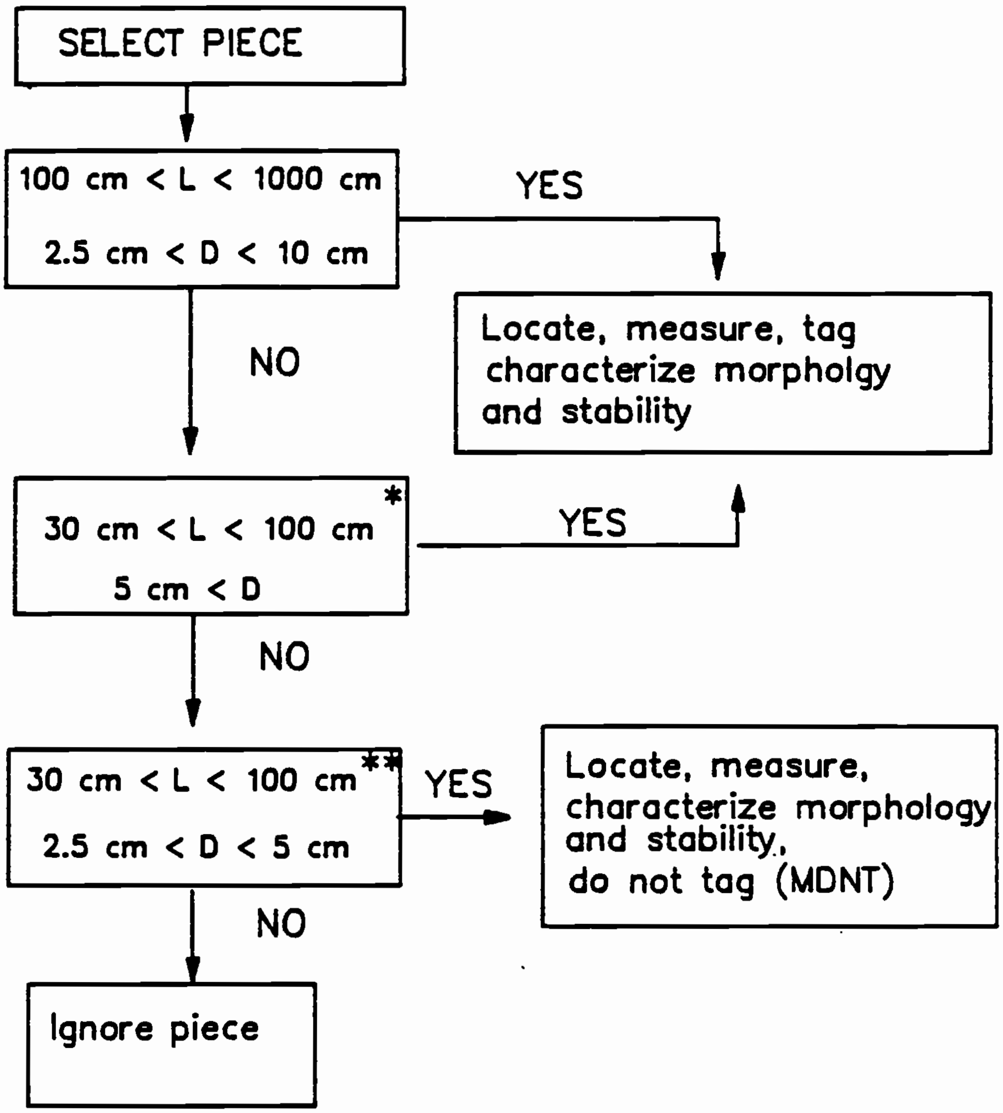
Bambi Creek (Appendix A). Succeeding surveys monitored their dispersion downstream. Only distance traveled from the release points and position in channel were recorded during fall surveys following the 1987 stake release. Succeeding surveys (July of 1988 and 1989) also recorded characterisitcs associated with stake mobility.

Definition of FWD

After a qualitative assessment of FWD present in both streams, FWD was defined using length and mean diameter criteria (Figure 2). Within this classification scheme, minimum piece size was 30 cm in length (L) x 2.5 cm in diameter (D). The maximum piece size was 10 m (L) x 10 cm (D). Due to the abundance of debris pieces 30 cm $< L <$ 100 cm and 2.5 cm $< D <$ 5.0 cm, it was deemed impractical to monitor in detail the movement of individual pieces in this size category. Consequently, these pieces were surveyed in an abbreviated manner relative to the others.

Piece Characterization

Each piece of FWD, with the exception of those in the abbreviated survey category (<u>m</u>easure but <u>d</u>o <u>n</u>ot "<u>t</u>ag", hereafter referred to as MDNT) was given a unique number which was affixed to the piece with a numbered metal tag. FWD pieces found between the CWD reaches on Beach Creek were not characterized.



*50 cm < L < 100 cm for Beach Creek

**50 cm < L for Beach Creek

Figure 2. Flow chart used to define FWD pieces for detailed measurements.

Fine woody debris was then evaluated based on five characteristics, with multiple descriptive categories in each (Appendix Table 2):

(1) Location in channel

a) The location of each piece within the channel was determined based on its distance (measured along the centerline) from the stream's confluence with Trap Creek. The confluence was assigned a channel distance of 0 meters.

b) Based on the methodology of Robison (1988), each piece was categorized as being in either channel Zone 1, 2, or 3+4 (Figure 3). These influence zones identified the vertical distribution of individual pieces within the channel. Fine woody debris in Zone 1 could influence fish habitat at low flow, in Zones 1 and 2 affect channel roughness at high flow, and in Zone 3+4 might enter the channel at some future date. If a piece extended through several zones, its volume distribution (in percent), by zone was ocularly estimated.

(2) Piece morphology

a) The length and mean diameter of each piece was measured. With branched pieces, the length was determined along the longest axis.

b) Piece complexity was evaluated using a ranking from 1 to 3. A complexity of "1" corresponded to a straight or bent piece,

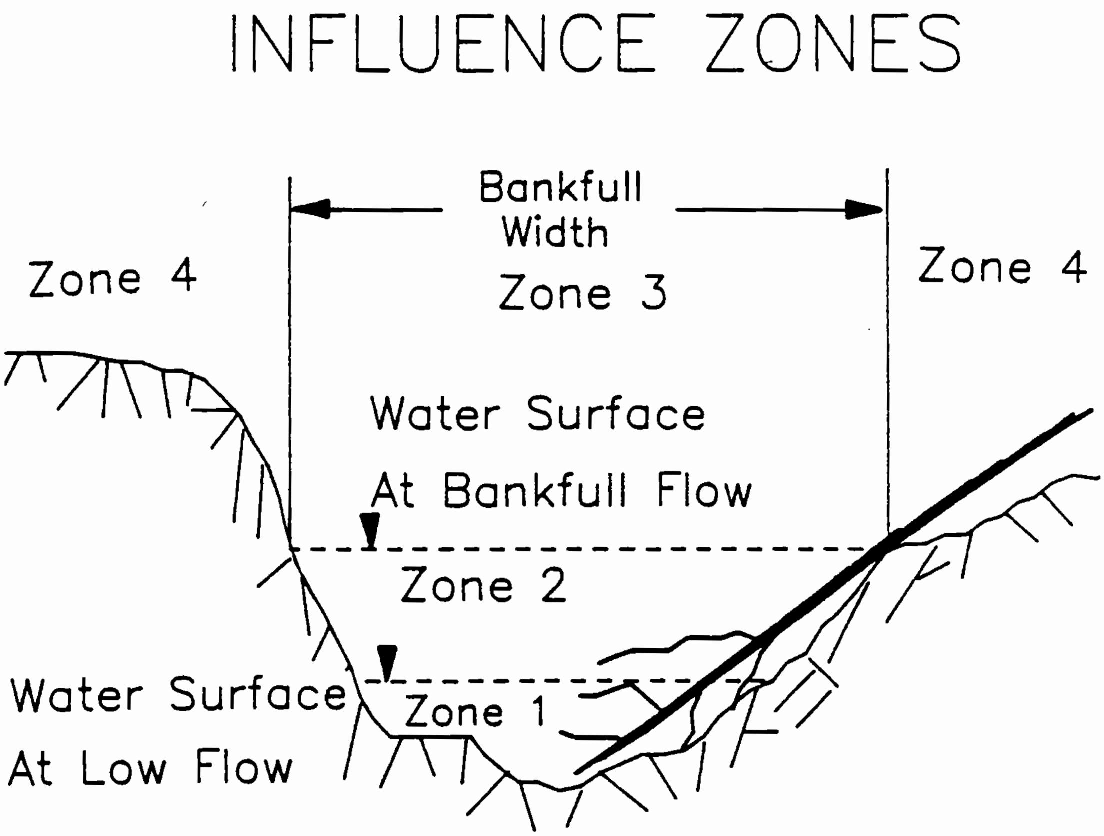


Figure 3. Influence zones used to characterize cross-section location of FWD (Adapted from Robison 1988).

"2" to one that was forked, and "3" to a piece with multiple branches (Appendix Table 2).

(3) Stability

To assess the potential for FWD movement under typical flow regimes, each piece was assigned a stability ranking from 1 to 3. A value of "1" corresponded to a piece judged to be easily entrained by frequent flows, a "2" represented a piece trapped by an element of roughness (held against the obstruction by the force of flow or attached to other stable elements), and "3" for a piece embedded in either a channel bank or bed substrate.

(4) Stability Agent

If a piece was judged to be either trapped or embedded (Stability 2 or 3), it was assigned a number from 1 to 10, each number corresponding to a different physical feature within the channel. Because FWD was often held immobile by several different agents, up to 2 values were assigned to each piece, in descending order of importance (Appendix Table 2).

(5) Decay Class

The state of decay of each piece was evaluated on a scale of 1 to 5, with 1 corresponding to little or no decay present and 5 to pieces in advanced states of decay. Criteria for decay class designation were based on twigs, bark, and texture characteristics (Appendix Table 2).

Estimation of FWD Volume

Individual FWD piece volume was estimated from length and diameter measurements using the equation for a cylinder. Because of the complex shape of some pieces, there was some inherent error in using this method. To ascertain the extent of this error, a manometer was used to determine true volume by water displacement. Approximately 150 pieces of FWD of varying complexity were first measured using field procedures, placed into the manometer, and the volume of the displaced water recorded.

RESULTS AND DISCUSSION

FLOW REGIME

Based on 9 years of flow data from Bambi Creek, beginning in 1980, yearly peak flow return intervals were calculated using a partial duration series with flows exceeding 1.0 m^3/s. The largest flow on record (2.30 m^3/s) occurred in 1980 and corresponded to a 10-year return interval. Table 3 lists the two largest flows for the fall of 1986 (one year before the commencement of the study), and their corresponding return intervals. Flows on each survey date and the largest flows recorded between them in 1987, and the two largest flows between the fourth and the fifth survey dates in 1988 and 1989 are also presented. From the table it is evident that peak discharges in 1986 were well below the magnitude of a 1-year event, approximately equal to a 1-year event in 1987, and slighty less in 1988.

STAKE RELEASES

Retention

Stake "retention" on a given survey date was quantified by dividing the number of stakes present by 100, (i.e., the number of stakes intially introduced), and exspressing the results as a percentage. To obtain a

Table 3. Selected peak flow and survey date discharges from a recording stream gage on Bambi Creek during the period 1986-1989.

Year	Date	Discharge (m^3/s)	Return Interval (yr)	Survey Number
1986	Nov. 5	0.43	<1.0	-
	Nov. 14	0.36	<1.0	-
1987	Sept. 18	0.10	<1.0	1
	Oct. 5	1.31	<1.0	-
	Oct. 19	0.07	<1.0	2
	Oct. 22	0.68	<1.0	-
	Nov. 1	0.08	<1.0	3
	Nov. 28	1.42	1.1	-
1988	July 23	0.06	<1.0	4
	Nov. 15	1.07	<1.0	-
	Nov. 29	1.28	<1.0	-
			<1.0	
1989	July 27	0.03	<1.0	5

consistent basis for comparison between Bambi Creek and Beach Creek's three reaches, stakes transported out of a specific reach in Beach Creek were excluded from this analysis.

The retention of released stakes varied between dates and streams over the period 1987-1989 (Figure 4), and appeared to be related to both storm flow and CWD loads. For both creeks, retention of stakes released in September of 1987 declined most dramatically between their introduction and the second survey in October of 1987. On Bambi Creek, 49% of the introduced stakes were transported out of the system in this period, while 89% were lost from CWD-1 on Beach Creek, 46% from CWD-2, and 0% from CWD-3. Peak stormflow during this period was 1.31 m^3/s on Bambi Creek and an estimated 0.63 m^3/s on Beach Creek. Between October of 1987 and November of 1987, the decline in percentage of stakes retained was less pronounced, and corresponded with smaller peak flows of 0.68 m^3/s on Bambi Creek and 0.33 m^3/s on Beach Creek. Except for CWD-3 on Beach Creek, the second greatest decline in stakes retained occurred between November of 1987 and July of 1988, when storm flow peaked at 1.42 m^3/s on Bambi Creek and 0.68 m^3/s on Beach Creek.

Coarse woody debris loads also appeared to influence stake retention. For the period between September of 1987 and July of 1989, retention of first release stakes on

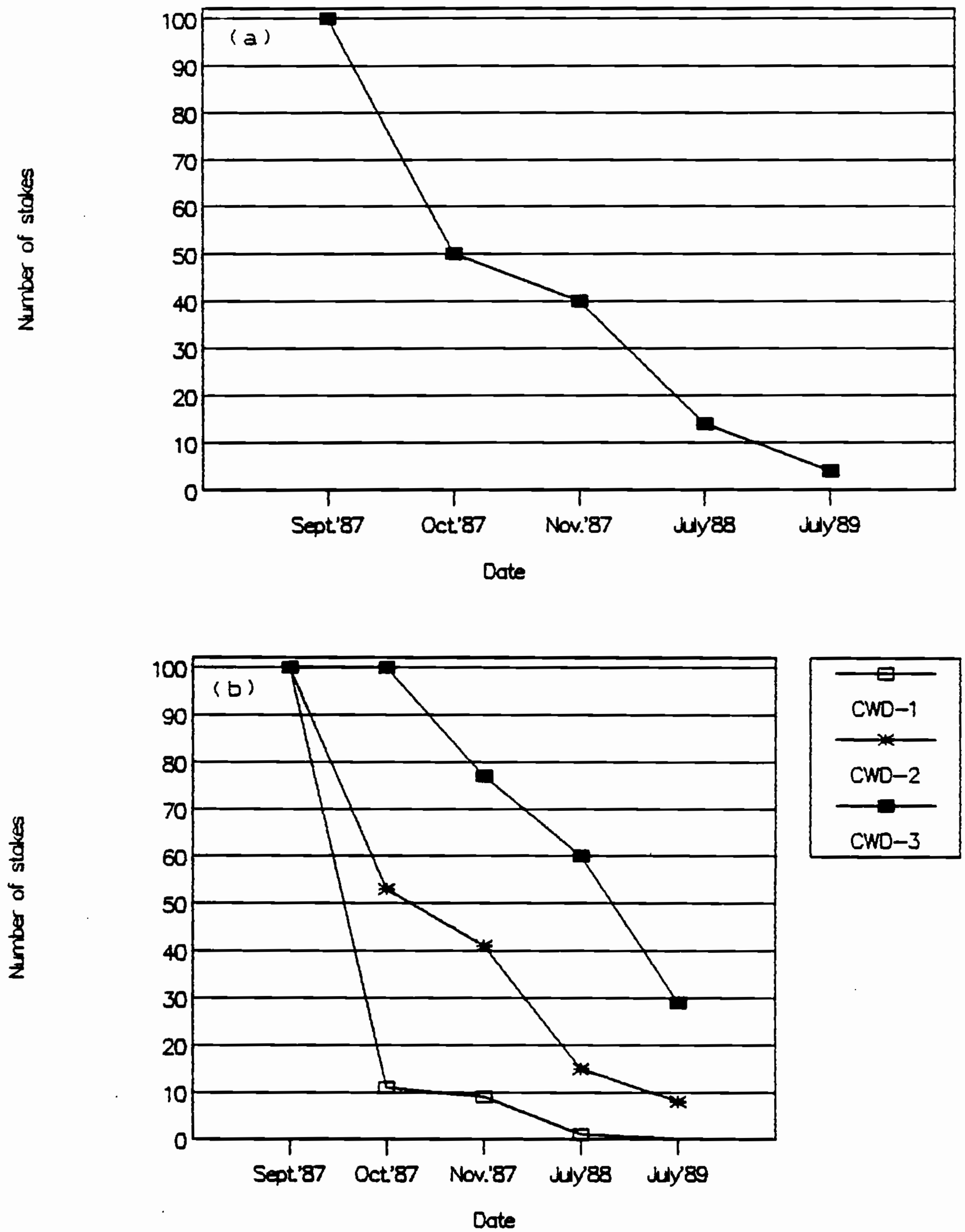


Figure 4. Number of stakes retained in (a) Bambi Creek and (b) CWD-1, CWD-2, and CWD-3, of Beach Creek following their release in September of 1987.

Beach Creek was consistently lowest in CWD-1, intermediate in CWD-2, and highest in CWD-3 (Figure 4b). Further, the temporal pattern of stake retention on Bambi Creek (Figure 4a), was markedly similar to that in CWD-2 on Beach Creek, whose Zone 1+2 CWD loads were only slightly less than that of the Main section on Bambi Creek (Table 2).

A comparison of retention values between the first and second stake releases indicated a measure of repeatability over comparable 1-year periods. Retention of stakes released in July of 1988 on Bambi Creek was 14% on July 1989; this compares to a retention of 15% for stakes released in September of 1987 and remeasured in July of 1988. The largest storm flow between July 1988 and July 1989 was 1.28 m^3/s. Stake retention was not as consistent on Beach Creek. The retention of stakes released in July of 1988 and remeasured in July of 1989 was 0% in CWD-1, 37% in CWD-2, and 37% in CWD-3. In contrast, the retention of stakes released in September of 1987 and remeasured in July of 1988 were 1%, 15% and 60%, respectively. The difference in the largest recorded peak flows between these two intervals (0.03 m^3/s) was not great, suggesting either varying retention between equivalent peak flows, the effects of a sequence of flows of varying magnitude, or the influence of flows which went unrecorded.

Dispersal

Stake dispersal downstream over time was characterized by measuring the downstream distance of stake travel from point of introduction and characterization of trapping sites at these distances. Stakes that were transported out of the system or in "hidden" storage were not accounted for.

The downstream dispersion of stakes is represented by a log-normal distribution for each survey date. Figure 5 shows a log-normal plot of probability density against distance on Bambi Creek for stakes released in September of 1987. The curves suggest two differing trends between survey dates. Between October and November of 1987, the probability peaks decreased and shifted to the right, suggesting a slight population shift of stake numbers downstream. The 1989 curve exhibits an increased peak with a shift to the left relative to previous curves. This occurred because the resident stakes (stakes remaining in the system) close to the release point remained stationary whereas those farther downstream continued to be moved by high flows.

The plot of probability density vs. distance for four survey dates and the three release points on Beach Creek revealed several trends (Figure 6). Critical distances, (distances at which their was a 25%, 50%, and

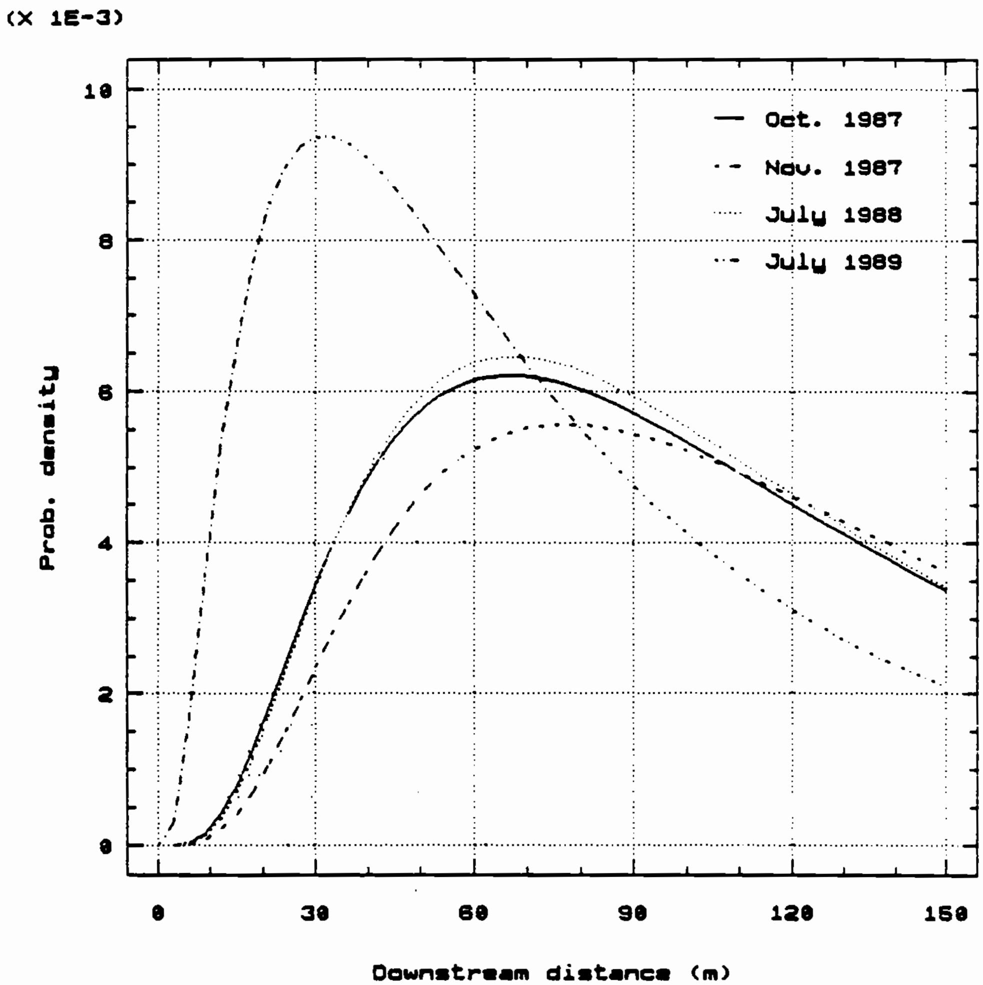


Figure 5. Probability density of stakes released in September of 1987 on Bambi Creek versus downstream distance for four measurement dates.

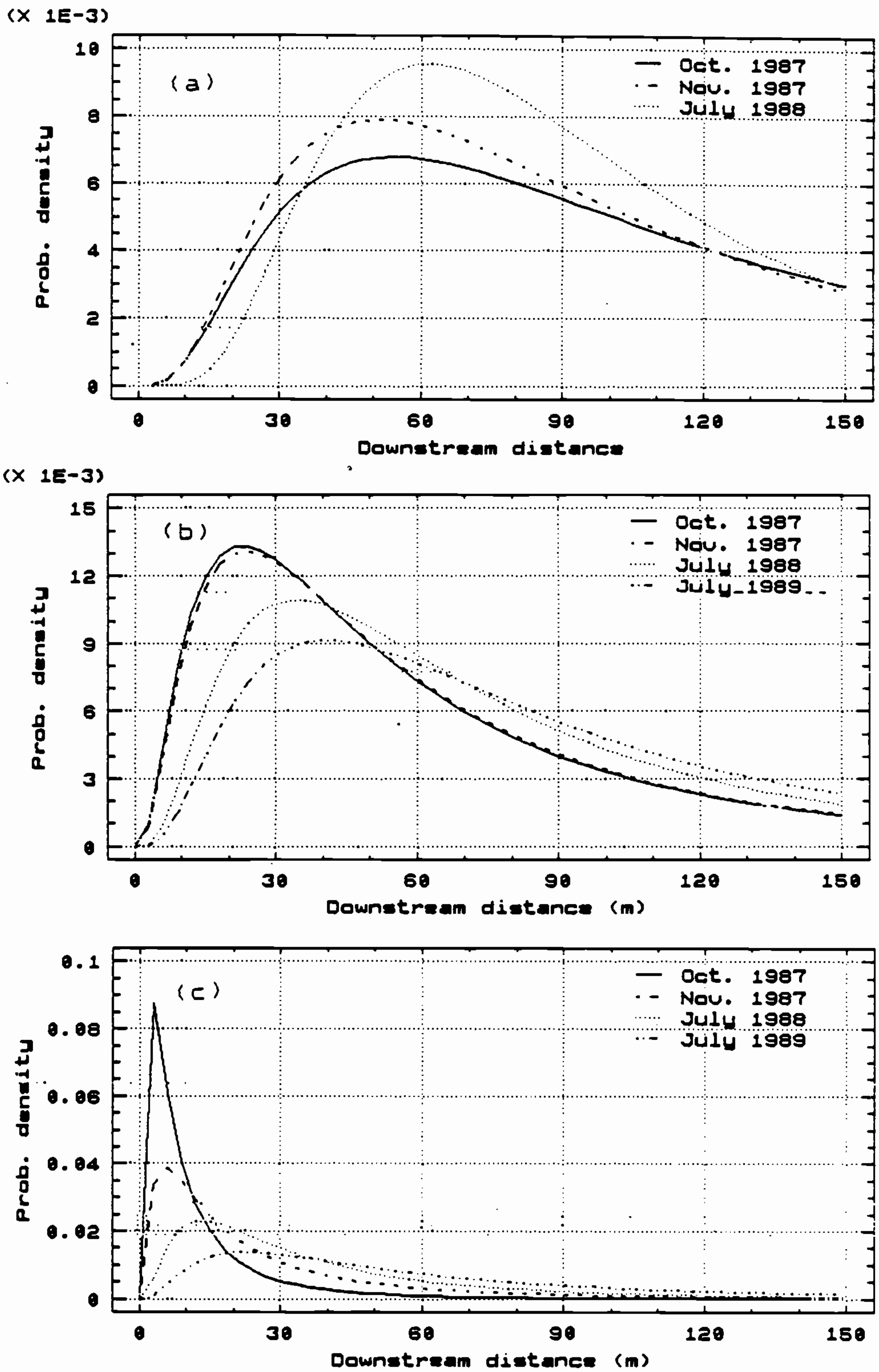


Figure 6. Probability density of stakes released in September of 1987 on Beach Creek versus downstream distance in (a) CWD-1, (b) CWD-2 and (c) CWD-3 for four measurment dates.

75% probability that the recovered stakes had traveled at least to that point) indicated that downstream dispersal was greatest for those stakes released at the head of CWD-1, intermediate in CWD-2, and smallest in CWD-3. This in part reflects the influence of the differing CWD loads directly downstream of the stake release points (Table 2), which appeared to be related to stake retention.

The series of probability curves (Figure 6) also illustrates a progressive downstream dispersal of stakes released at the head of CWD-2 and CWD-3. Similar to Bambi Creek, the density peak shifts in CWD-1 were not as consistent, and were largely attributable to stake movement out of lower portions of the stream while those remaining moved only short distances downstream from the release point.

A plot of cumulative frequency (summation of number of stakes present on a given date divided by 100) vs. downstream distance for Bambi Creek (Figure 7) illustrates the role of individual capture and storage sites over time on the dispersal of stakes released in September of 1987. Sharp increases in cumulative frequency at a given distance represent sites which captured multiple stakes. These increases, (e.g. at 33 m, 187 m, and 290 m), often showed repeatability between stake releases and survey dates. Generally, the low total cumulative frequency and the drawn-out nature of the curves suggested long

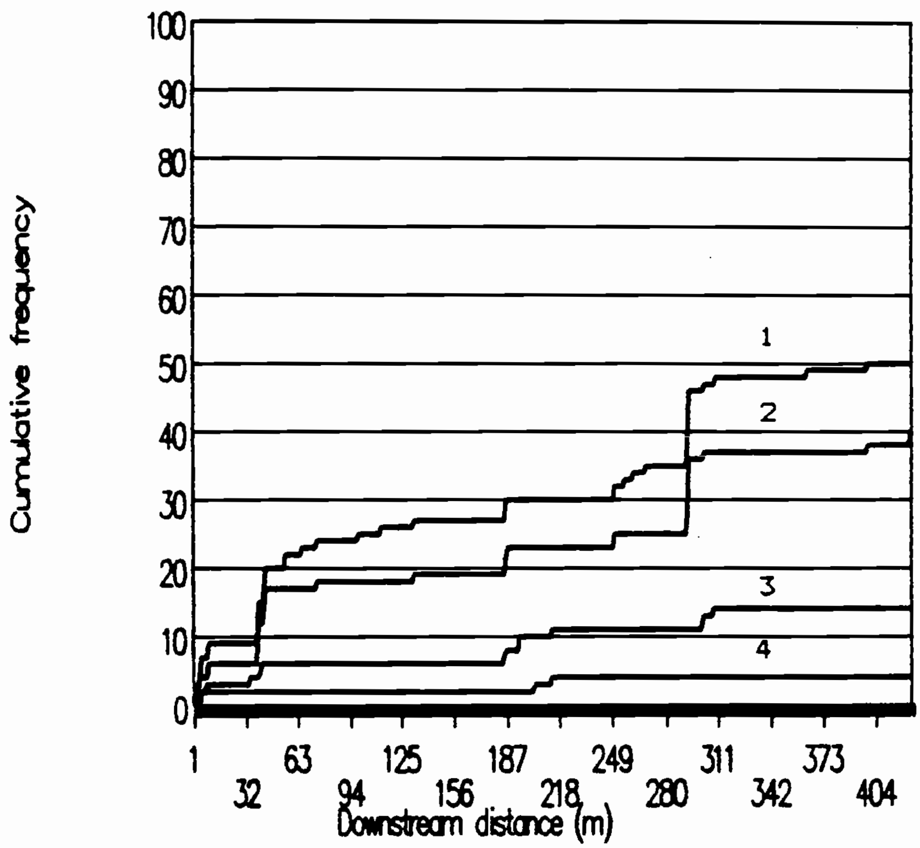


Figure 7. Cumulative frequency of recovered stakes released in September of 1987 versus downstream distance for Bambi Creek on four survey dates. (Note: 1=October of 1987, 2=November of 1987, 3=July of 1988 and 4=July of 1989).

dispersal distances and sporadic stake capture. The cumulative frequency curve for stakes in the second release (July of 1989) was virtually identical with the July of 1988 curve from the 1987 release.

The cumulative frequency curves for Beach Creek (Figure 8), revealed more and larger cumulative frequency increases than were evident on Bambi Creek. For example, at a distance of approximately 48 m in Figure 8c., a sharp increase in cumulative frequency is noted for each survey date. This corresponded to a cluster of three channel-spanning pieces of CWD, each with multiple branches that extended well down into a pool and representing a natural "trash-rack" which was effective in capturing stakes floating downstream. Another example is at a site corresponding to a downstream distance of 20 m in Figure 8b and 106 m in Figure 8c, (because some stakes travelled downstream and were captured in a lower reach, downstream distances in Figures 8a,b, and c overlap,). At this site a cluster of two partially embedded and decayed pieces of CWD which were causing significant capture and storage of stakes introduced at the head of both CWD-3 and CWD-2. Conversely, the relative lack of significant capture sites in and downstream of CWD-1 are reflected in the relatively flat trajectory of the cumulative frequency curves in Figure 8a.

The cumulative frequency curves for stakes in the

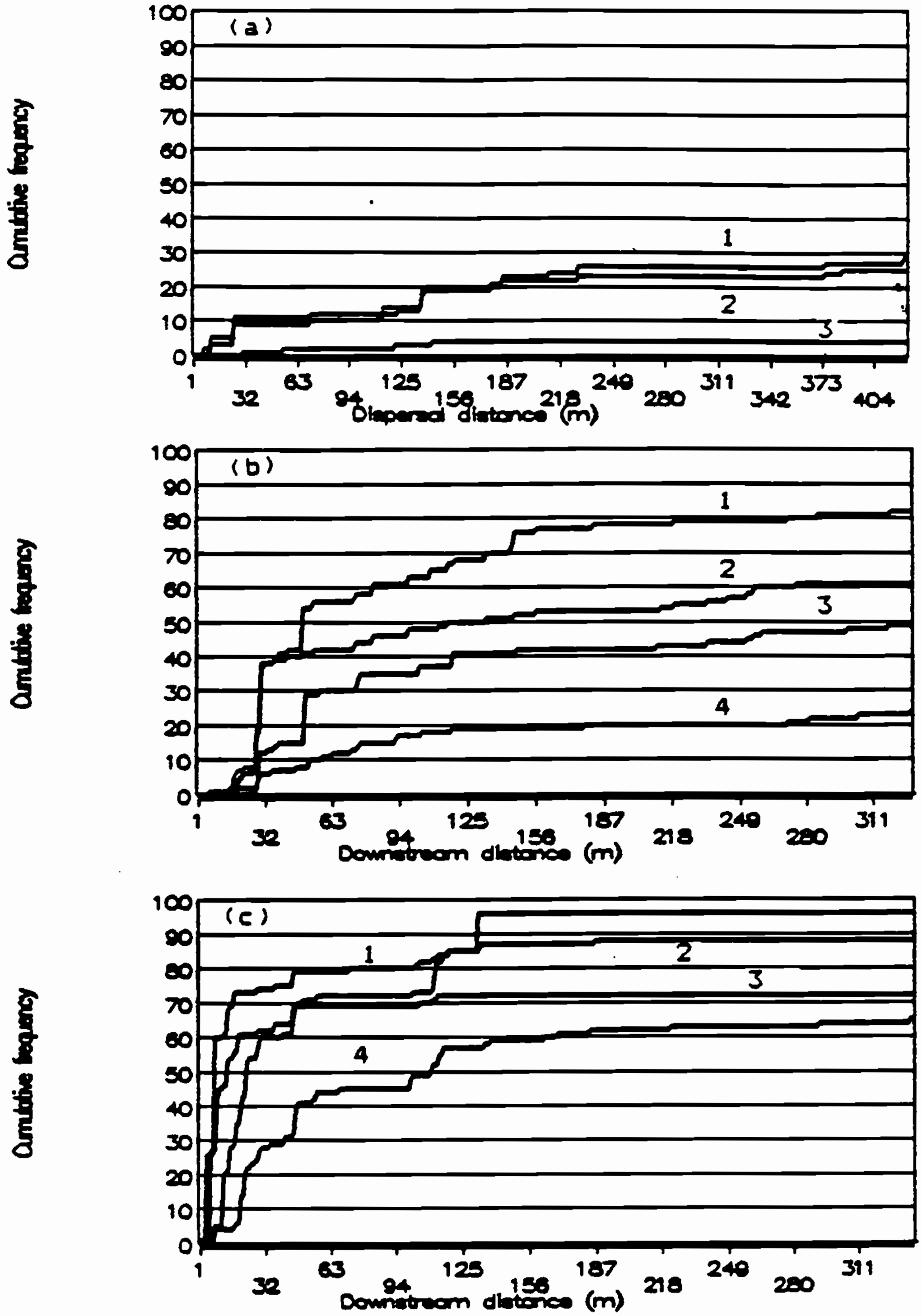


Figure 8. Cumulative frequency of recovered stakes introduced at the head of (a) CWD-1, (b) CWD-2, and (c) CWD-3 on Beach Creek versus downstream distance on four survey dates. (Note: 1=October of 1987, 2=November of 1987, 3=July of 1988, and 4=July of 1989).

July of 1988 release showed similarity to those in the first release (Figure 9). The curve for stakes introduced in CWD-1 (Figure 9a) has a noticeably flat trajectory, while CWD-2 (Figure 9b) and CWD-3 (Figure 9c) reflects sites where multiple stakes were captured. For stakes in both releases, the same capture sites were important.

Trapping Characteristics

The small number of stakes recovered in 1988 and 1989 in Bambi Creek indicated an absence of channel features capable of and storing stakes longer than one year. Of the stakes released in September of 1987, the largest percentage of stakes were trapped (Table 4; Stability class and Stability agent were not recorded during the 1987 surveys). Stakes in the July of 1988 release were either mobile or embedded in July of 1989. Of those embedded in 1988, (three stakes total), two were embedded in the channel banks and one in an accumulation of particulate organic matter rather than bed substrate. All of the the embedded stakes in the July of 1988 release were embedded in gravel and silt.

Except for 1988, CWD was not a frequent stability agent. For stakes released in September of 1987, undercut banks were important trapping agents in 1988 and 1989, but were not for the stakes released in July of 1988.

The frequencey distributions of stakes between

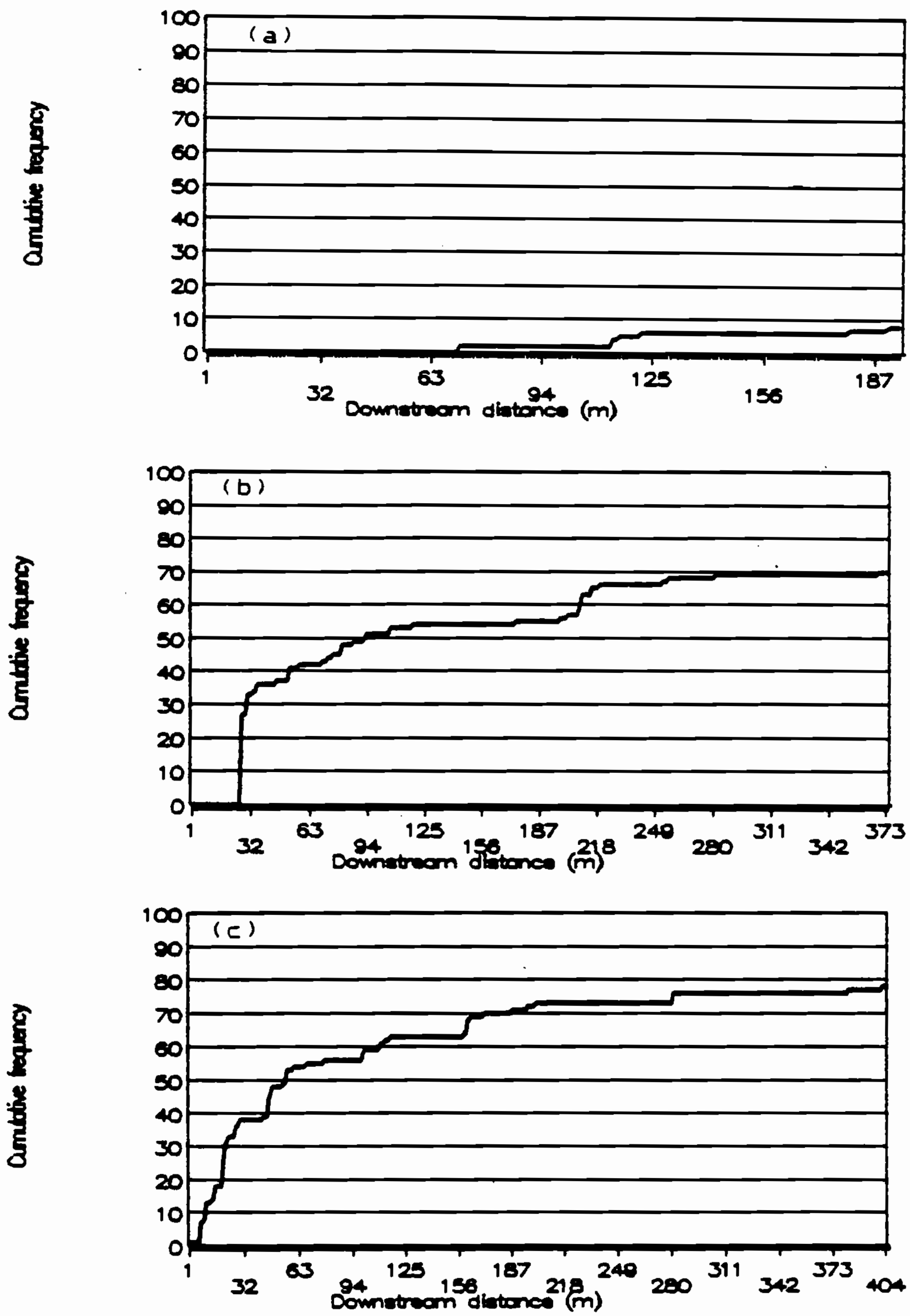


Figure 9. Cumulative frequency of recovered stakes released at the head of (a) CWD-1, (b) CWD-2, and (c) CWD-3 on Beach Creek in July of 1988 versus downstream distance.

Table 4. Characteristics associated with stakes recovered from the September of 1987 and July of 1988 stake releases on Bambi Creek.

Characteristic	1987 Release		1988 Release
Survey year	1988	1989	1989
Number	14	8	15
Stability class			
None (%)	36	25	67
Trapped (%)	50	50	0
Embedded (%)	14	25	33
Stability agent 1			
None (%)	36	25	67
CWD (%)	29	0	0
Banks (%)	14	50	0
Embedded (%)	0	25	33
Zone of Influence			
Zone 1+2 (%)	50	50	47
Zone 3+4 (%)	50	50	53

influence Zones 1+2 and 3+4 were approximately equal for all recovered stakes (Table 4). Stakes found in Zone 3+4 were often several meters away from the active channel at low spots in the channel banks, suggesting trapping during overbank flows.

In the Beach Creek reaches, the majority of stakes in the release of September of 1987 were either trapped or mobile (Table 5). Within these two classes, trapped stakes averaged 77.3% [± 14.2%], i.e. mean [± 1 standard deviation], and 22.0% [± 14.5%] mobile. The notable absence of embedded stakes may be due to their floatable nature. During entrainment, it is possible that they travelled high in the water column, making it less likely that they would be trapped near the channel bottom where bedload burial could occur. However, at one site in CWD-2, 20 stakes released in July of 1988 were initially wedged between several pieces of partially embedded and decaying CWD and then largely buried by gravel which accumulated behind them. This is reflected in Table 4, in the "other" category, under Stability agent 2.

Stakes from the September of 1987 release were often trapped by CWD and FWD, the two most frequent stability agents in 1988 and 1989 (Table 5). Roots were a frequent stability agent associated with stakes released at the head of CWD-2. A secondary stability agent (Stability agent 2), was not common for most of the stakes. The

Table 5. Characterisitics associated with stakes recovered from the September of 1987 release in CWD-1, CWD-2, and CWD-3 on Beach Creek.

	1988			1989		
Characteristic	CWD-1	CWD-2	CWD-3	CWD-1	CWD-2	CWD-3
Number	5	49	89	0	24	66
Stability class						
Mobile (%)	40	14	16	0	42	32
Trapped (%)	60	86	83	0	58	66
Embedded (%)	0	0	1	0	0	2
Stability agent 1						
None (%)	40	14	16	0	42	32
CWD (%)	0	10	45	0	17	36
FWD (%)	30	39	32	0	17	20
Roots (%)	0	35	0	0	13	0
Other (%)	30	2	7	0	11	12
Stability agent 2						
None (%)	80	69	76	0	70	77
Other	20	31	24	0	30	23
Zone of Influence						
Zone 1+2 (%)	42	67	57	0	71	73
Zone 3+4 (%)	58	33	43	0	29	27

trapping characteristics associated with stakes measured in July of 1988 were similar to those measured in July of 1989.

The majority of all stakes were found in influence Zones 1+2 (Table 5). Those recovered in Zones 3+4 were often on the floodplain near low spots in the channel banks or on the floodplain terrace behind in-channel, bank-to-bank obstructions of CWD. The latter observation may suggest that stakes stored in backwater locations, behind channel obstructions, may have been deposited overbank during the falling hydrograph limb. Likewise, it is conceivable that entrainment of floatable floodplain debris may occur in this manner, especially when the backwater elevations exceed the obstruction height on the rising limb of the hydrograph. Zone 3+4 stakes were at a height above the low water surface ranging from 24 to 64 cm and at a distance of 0.5 to 10 m from the nearest bank.

CHANGES IN FWD STORAGE

Bambi Creek

The number of FWD pieces in Bambi Creek were categorized and tabulated for the dates September of 1987, and July of 1988 and 1989 (Appendix Table 3). Based on FWD piece type and survey date, each piece was associated with one of four groups. Those tagged in 1987 and 1988 are referred to as Tag '87 and Tag '88, respectively. Tag '89 pieces are those which fit the tagging criteria but were not tagged because of study termination. The MDNT pieces inventoried in 1987-1989 were characterized but not tagged.

Individual piece volume was calculated using the equation for a cylinder with individual piece length (L) and diameter (D). The accuracy of this estimate was tested by linearly regressing 148 natural log transformed calculated piece volumes against the same pieces true volume determined by water displacement. The regression produced a best-fit line with the equation $\ln Y = 0.77 + 0.88 \ln X$, with $r^2 = 73$. True volumes ranged from 180 to 6020 cm^3. An average measured piece volume in this study was approximately 3000 cm^3; the above equation indicates that true volumes were underestimated by approximately 17%.

FWD loads on Bambi Creek generally declined over the period 1987-1989, with a 71% total net loss in number of and 47% net loss in volume (Appendix Table 3). The period 1987-1988 experienced the greatest decline in both numbers and volume of all tagged and MDNT pieces (Figure 10). Total piece numbers fell by 56% and volume by 41%. For the following period (1988-1989), the rate of decline decreased to 43% and 9% respectively. The difference in largest recorded peak flow between these two periods was

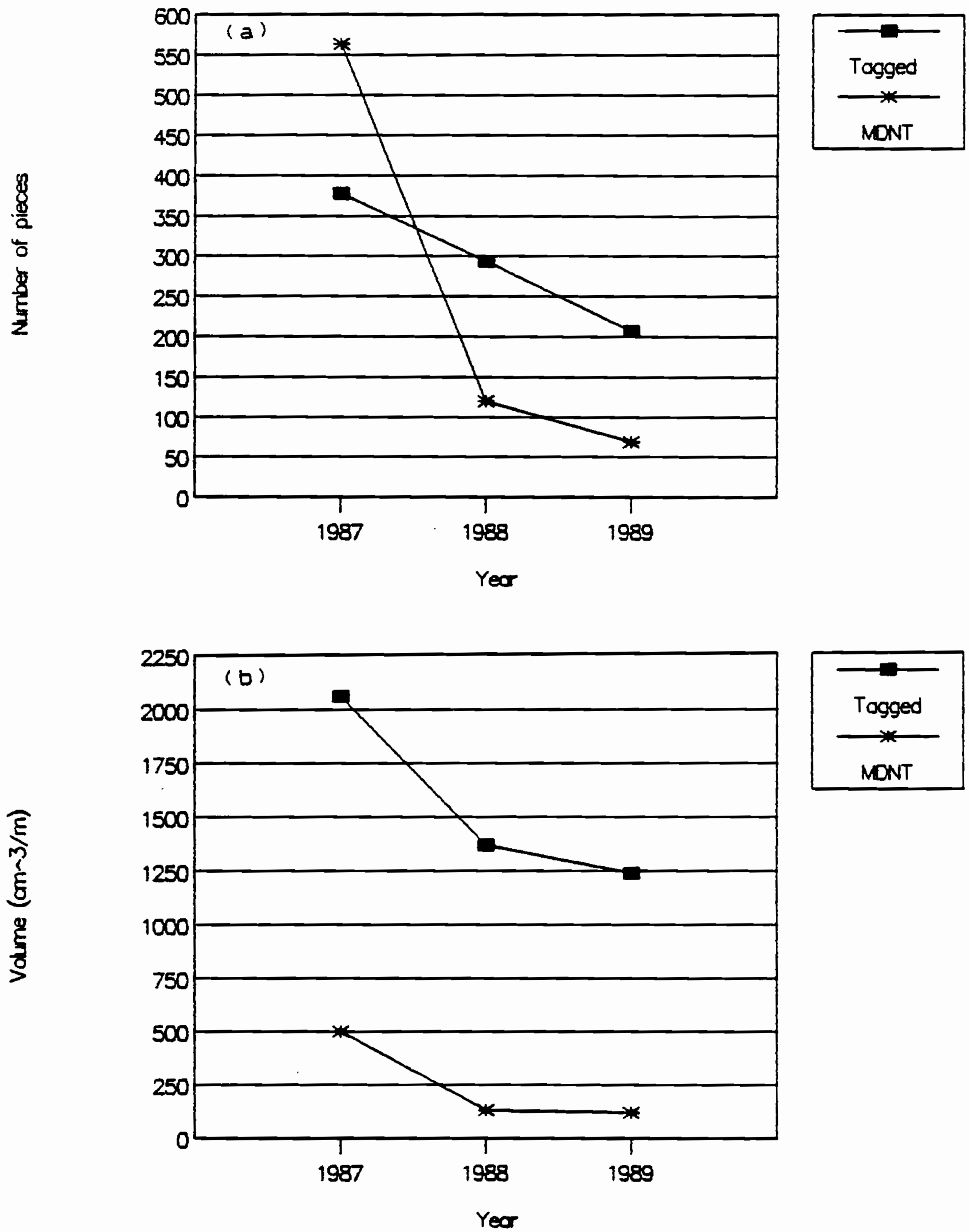


Figure 10. (a) Number and (b) volume of tagged and MDNT pieces stored in Bambi Creek over a three year period.

0.14 m^3/s, with the largest flow in the first period.

Tag '87 pieces experienced a 67% loss in numbers resident between 1987 and 1989, representing a volume loss of 72%. An 88% decline in MDNT numbers between 1987-1989 was the greatest decline of any category of FWD. However, because of their smaller dimensions relative to the other piece types, their contribution to the total decline in volume over the same period was not great (Figure 10b).

The above data indicate that changes in FWD loads between years were not uniform, despite recorded peak flows which did not vary greatly between periods, and further, that FWD "exports" far exceeded inputs between 1987 and 1989. However, by 1989, approximately 50% of the resident FWD was "new" relative to the study's beginning in September of 1987. In 1989 the contribution of Tag '87 pieces to the total resident load of FWD was 580 cm^3/m (43% of total), compared to 660 cm^3/m (49%) for the combined Tag '88 and Tag '89. It is unknown what percentage of the remaining 120 cm^3/m (8%) was attributable to MDNT which was resident for the study duration, but the sharp decline in MDNT pieces relative to the tagged pieces suggests a high degree of turnover.

Four sections of Bambi Creek (i.e., Intertidal, Central, Cleaned, and Upper) were designated for comparing relative loadings of FWD with CWD in influence Zone 1+2. Section locations, lengths, characteristics, and CWD and

FWD loads are given in Appendix Table 1. The FWD loads in Figure 11b were calculated by dividing the total volume in a section by its respective length. Over the period 1987-1989, the sections with high CWD loads had greater than average Tag '87 loads (Figure 11). Of the two reaches without CWD loads, the Cleaned section had greater FWD loads than the Intertidal. Lack of significant loading in the Intertidal section may be explained by an absence of channel roughness elements, particularly CWD, regular tidal "flushing", and a lack of terrestrial inputs.

Another trend evident in Figure 11 is greater Tag '87 storage in the Upper section relative to the Central section. The ratio of average Tag '87 load for the period 1987-1989 in the Upper section to the Central section was 2.6:1, while the analogous ratio for CWD loads was 4.6:1. This suggests a non-proportional relationship between amount of FWD volume stored and CWD loads. A comparison of these two section's FWD loads to the Intertidal and Cleaned sections' strongly suggests an important link between the presence of Zone 1+2 CWD loads and FWD storage.

Beach Creek

Similar to the findings on Bambi Creek, Beach Creek also appeared to be exporting more FWD than it was storing between 1987 and 1989. All reaches, with the exception of

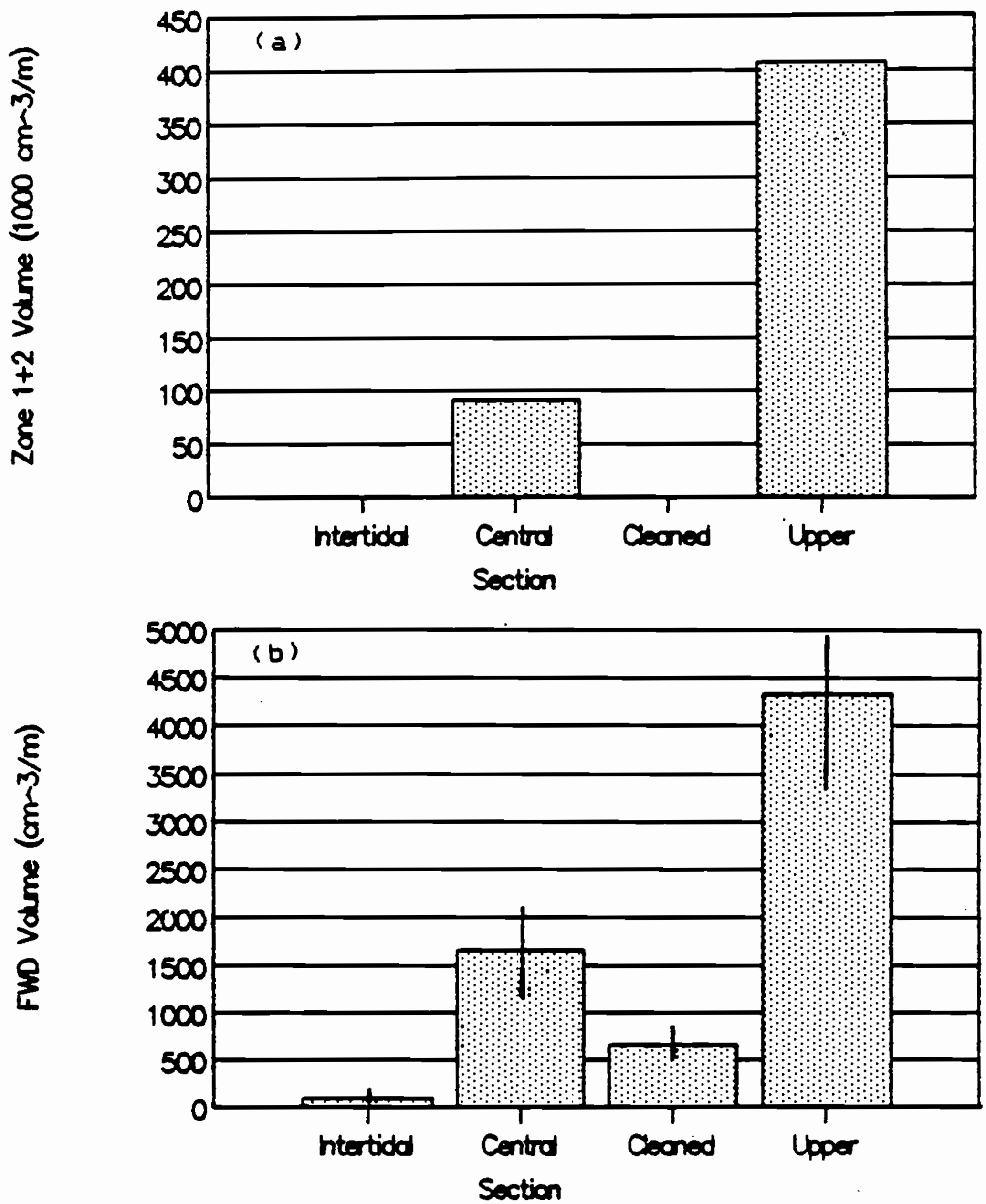


Figure 11. (a) CWD loadings in influence Zone 1+2 and (b) three-year average Tag '87 FWD loading for four sections ofBambi Creek (error bars represent 1 standard deviation).

CWD-2, showed a yearly decline in total number of FWD pieces present (Appendix Table 4, Figure 12a). CWD-2 had a net gain (all piece types) of 35 pieces between 1988 and 1989. This gain was also associated with a 320% increase in MDNT over the previous year; MDNT in the other two reaches declined on a yearly basis (Appendix Table 4). Tag '87 pieces for all reaches declined in number by 56% and MDNT by 69% between 1987 and 1989. Yearly declines in total piece numbers by reach were greatest over the 1987-1988 period; CWD-1 had a net loss of 36%, CWD-2 51%, and CWD-3 33%. In contrast, from 1988 to 1989, CWD-1 experienced a net loss of 13%, CWD-2 a net gain of 33%, and CWD-3 a net loss of 25%. Retention of Tag '87 pieces between 1987 and 1989 was 35% in CWD-1, 40% in CWD-2, and 49% in CWD-3. The percent retention of stakes released in September of 1987, and re-measured in July of 1988, though differing in value, also reflected this pattern of lowest to highest values from CWD-1 to CWD-3, in correspondance with respective CWD loadings.

In conjunction with the decline in piece numbers, all three reaches showed a net decline in stored FWD volume during the period 1987-1989. The greatest decline occurred during the 1987-1988 period (Figure 12b), which was consistent with the findings on Bambi Creek. Over the next one-year period (1988-1989), FWD loads in CWD-3 declined 8% while CWD-1 and CWD-2 showed net volume

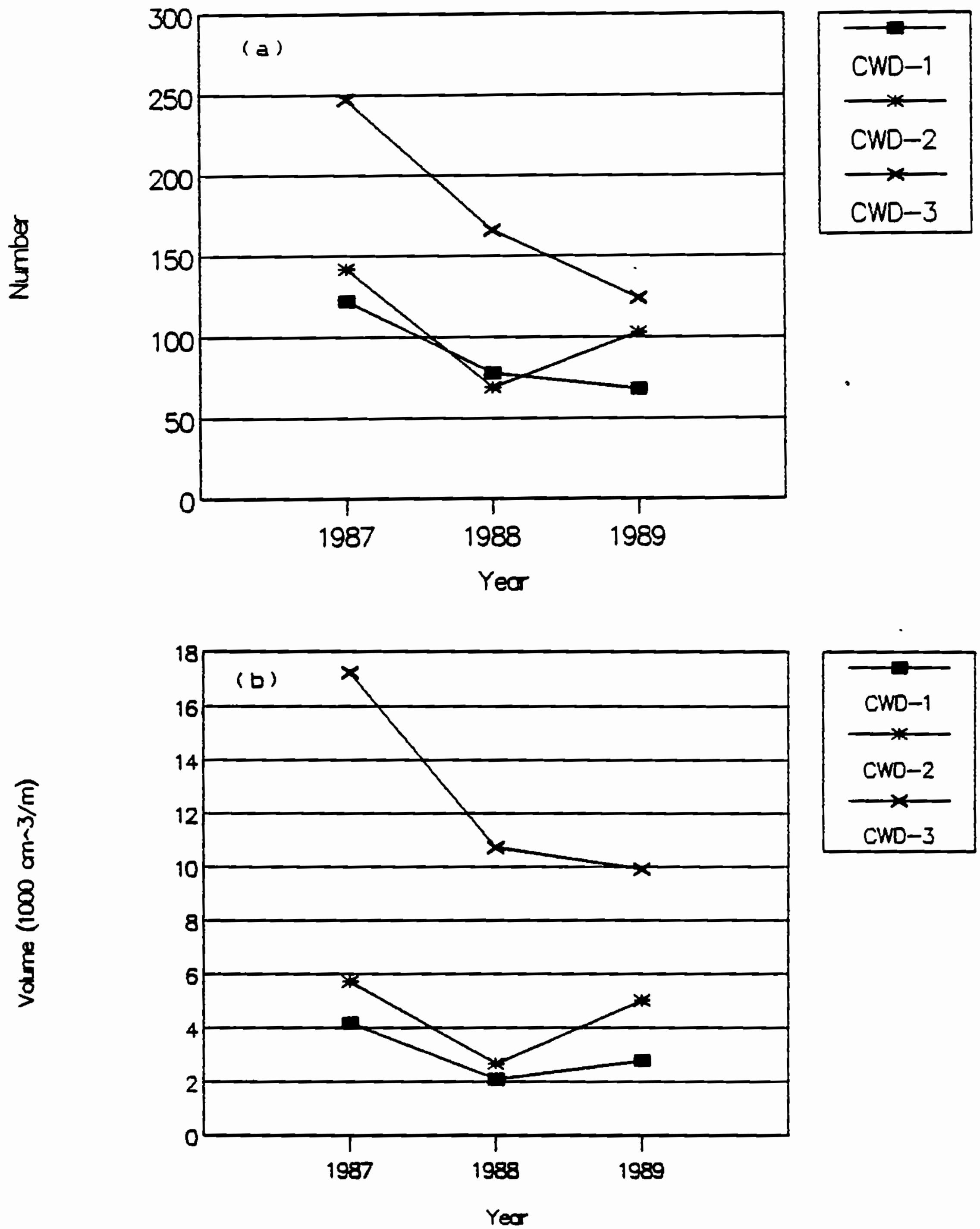


Figure 12. (a) Number and (b) volume of FWD pieces stored in CWD-1, CWD-2, and CWD-3 on Beach Creek over a three-year period.

increases of 25% and 47% respectively.

Yearly changes in piece numbers and volumes for all types of FWD in all three reaches are illustrated in Figure 13. This figure illustrates the predominance of Tag '87 pieces in both number and volume as a fraction of all pieces between 1987-1989. Further, it indicates an elevated level of FWD inputs in 1989 relative to 1988; Tag '89 pieces were greater in both number and volume than either Tag'88 or MDNT pieces. This suggests non-uniform inputs into the stream between years.

In CWD-1, all categories of FWD pieces except Tag '89 showed decreases in volume present, indicating that this category was largely responsible for the net volume increase in 1989 over 1988 (Appendix Table 4). The increase in stored FWD volume in CWD-2 from 1988 to 1989 was partially attributable to a volume increase in Tag '87 pieces, despite a loss of 8 pieces that were present in 1988. Bedload scour may have uncovered previously embedded Tag '87 pieces during the fall and winter storms of 1988, creating an apparent volume increase in this group. The Tag '87 volume represented 30% of the total net increase of 2360 cm^3/m for all piece types. The majority of the net volume increase (65%) was attributable to Tag '89 pieces.

Though total piece numbers in CWD-3 declined 25% (from 166 to 124) from 1988 to 1989, the decline in total