RESEARCH

Effects of Recent Volcanic Eruptions on Aquatic Habitat in the Drift River, Alaska, USA: Implications at Other Cook Inlet Region Volcanoes

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ABSTRACT Numerous drainages supporting productive salmon habitat are surrounded by active volcanoes on the west side of Cook Inlet in south-central Alaska. Eruptions have caused massive quantities of flowing water and sediment to enter the river channels emanating from glaciers and snowfields on these volcanoes. Extensive damage to riparian and aquatic habitat has commonly resulted, and benthic macroinvertebrate and salmonid communities can be affected. Because of the economic importance of Alaska's fisheries, detrimental effects on salmonid habitat can have significant economic implications. The Drift River drains glaciers on the northern and eastern flanks of Redoubt Volcano. During and following eruptions in 1989–1990, severe physical disturbances to the habitat features of the river adversely affected the fishery. Frequent eruptions at other Cook Inlet region volcanoes exemplify the potential effects of volcanic activity on Alaska's important commercial, sport, and subsistence fisheries. Few studies have documented the recovery of aquatic habitat following volcanic eruptions. The eruptions of Redoubt Volcano in 1989–1990 offered an opportunity to examine the recovery of the macroinvertebrate community. Macroinvertebrate community composition and structure in the Drift River were similar in both undisturbed and recently disturbed sites. Additionally, macroinvertebrate samples from sites in nearby undisturbed streams were highly similar to those from some Drift River sites. This similarity and the agreement between the Drift River macroinvertebrate community composition and that predicted by a qualitative model of typical macroinvertebrate communities in glacier-fed rivers indicate that the Drift River macroinvertebrate community is recovering five years after the disturbances associated with the most recent eruptions of Redoubt Volcano.

Commercial and sport fishery resources of the Cook Inlet region are economically important to the State of Alaska and generate hundreds of millions of dollars annually. Additionally, many local residents rely on the fisheries for subsistence and recreation. The sockeye, chinook, coho, pink, and chum salmon fisheries in the Cook Inlet region thrive because much of the surrounding land is undeveloped, water quality is unimpaired, and seasonal streamflows are adequate to support abundant diverse spawning and rearing habitat. Significant challenges for managers of this fishery are to ensure that adequate riverine habitat is available to support the fish, that adequate escapements are allowed into the rivers and estuaries to sustain the population, and that adequate allocations of the remaining fish are made in a fair way among the various users. This management challenge is undertaken with a series of tools that includes regulating subsistence, sport, and commercial fishing and land uses. However, aligned along the western side of Cook Inlet are five active volcanoes (Figure 1) that need to be considered in this management paradigm. These volcanoes have combined to produce more than 90 volcanic eruptions during the last 10,000 years (Riehle 1985). Recent eruptions at several of these volcanoes have significantly affected water quality (Mathisen and Poe 1978, Whetstone 1955, 1956, Wilcox 1959), changed channel geometry (Dorava and others 1993, Waythomas and Dorava 1999), and destroyed riparian vegetation (Dorava and Meyer 1994). These volcanogenic alterations decrease habitat value or degrade it beyond use and many of the physical changes can persist for years (Meyer and Martinson 1989).

KEY WORDS: Aquatic habitat; Volcanoes; Lahars; Lahar-runout flows; Macroinvertebrates; Community structure; Community composition; Taxonomic similarity

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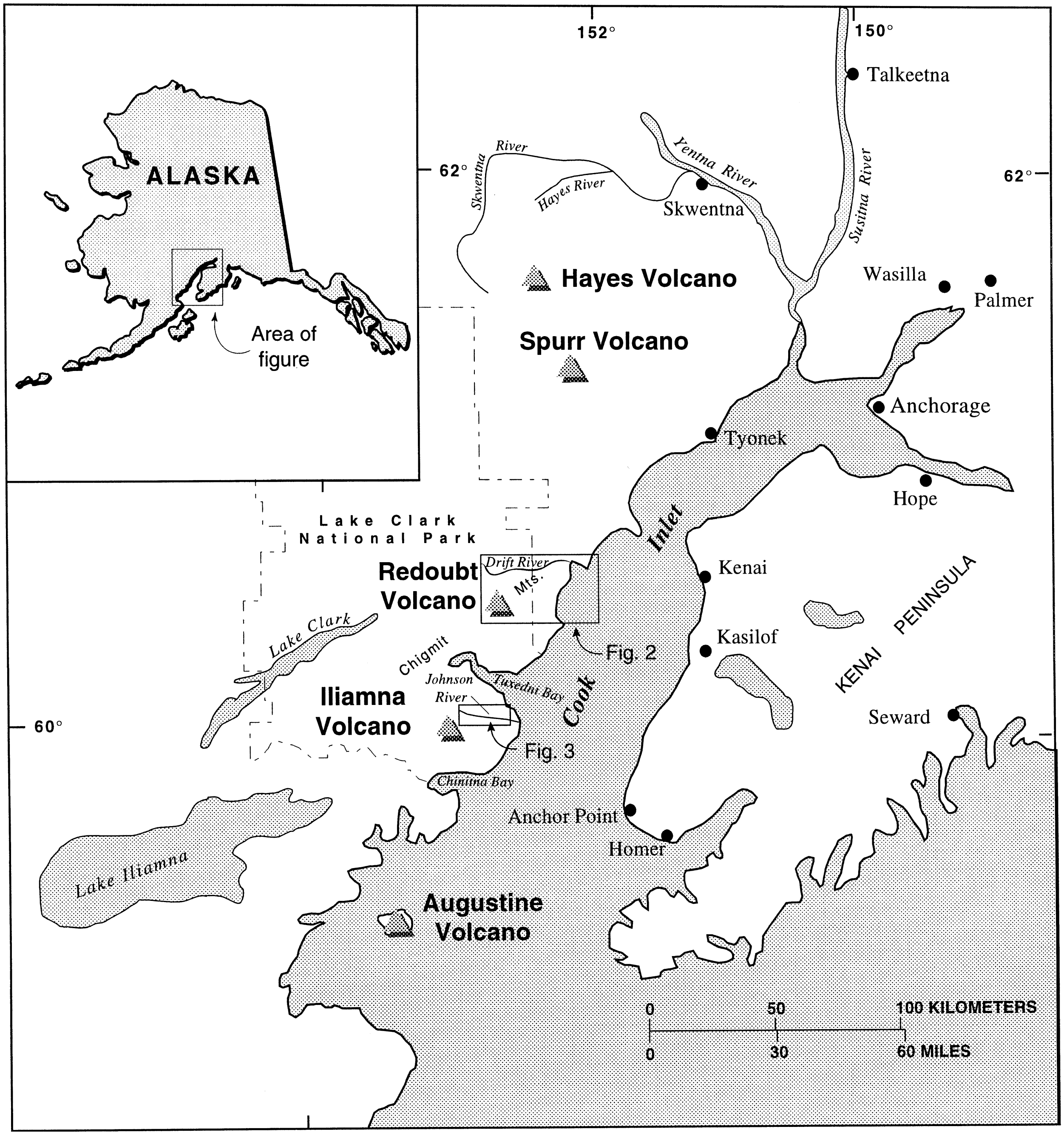


Figure 1. Active volcanoes of the Cook Inlet Region, Alaska.

Numerous streams draining volcanoes in the Cook Inlet region provide productive aquatic habitat (Russell and National Park Service 1980). Because eruptions in the Cook Inlet region are relatively frequent—Augustine, Spurr, and Redoubt volcanoes have all erupted during the past decade—it is difficult to assess the effects of an individual eruption on the regional fishery. Without population information before and after an eruption, it is also difficult to assess the effects of an eruption on salmon productivity from a specific drainage. Assessing the abundance and distribution of the macroinvertebrate community in these rivers can integrate the aquatic habitat conditions over temporal and spatial scales. This assessment also indicates the ability of a river to support lower trophic level species and thus provide food for upper trophic levels.

The recovery of biotic communities in rivers following major volcanogenic disturbances in Alaska has not previously been examined. In general, the macroinvertebrates in Alaska are taxonomically sparse compared with those in other North American lowland rivers at lower latitudes (Oswood and others 1995). The likely ecological factors that influence this sparseness include at least the following: ability to withstand freezing, physiological ability to sustain growth and reproduce in the face of low cumulative degree-days, and low availability of carbon to river food webs (Oswood and others 1995). The lower mean annual temperature and lower water temperature in higher latitudes also appear to play a major role in determining the abundance and distribution of macroinvertebrates in Alaska (Oswood and others 1995).

Based on numerical abundance, macroinvertebrate fauna in south-central Alaska are most commonly from the order Ephemeroptera (mayflies), followed closely by Diptera (trueflies), and in lower numbers by Plecoptera (stoneflies) and Trichoptera (caddisflies) (Oswood and others 1995). For rivers of glacier origin, the occurrence of macroinvertebrate fauna shifts slightly so that Diptera are the most common followed by Ephemeroptera, Plecoptera, and few or no Trichoptera (Milner and Petts 1994).

The streams draining volcanoes in the Cook Inlet region are commonly fed by glaciers and their channels are frequently unstable and shifting, with considerable streambed movement. These glacier-fed rivers generally provide a migratory pathway for salmon to access clearwater tributaries, where habitat is more suitable. However, glacier-fed rivers can also provide complex and valuable habitat for salmonids. Braided reaches provide an abundance of shallow riffle areas, which are excellent spawning habitat because adequate water flows through the streambed gravels providing oxygen for incubating salmon eggs. Rearing habitat is provided primarily by river margins, in off-channel ponds and sloughs, or in tributaries where water temperatures are higher and turbidity is lower than those in the mainstem of the river. Milner and Petts (1994) suggest that macroinvertebrate communities in glacier-fed rivers show deterministic patterns and that the principal variables controlling macroinvertebrate community composition and structure are water temperature and channel stability. Their model predicts an abundance of specifically adapted macroinvertebrates as river channels become more stable and water temperatures remain lower than 2°C. Initial colonizers of glacier-fed rivers are Diptera, chironomids of the genus *Diamesa*. As distance from the glacier source becomes greater, river temperatures increase and channels become more stable, resulting in a subsequent predicted increase in macroinvertebrate numbers and diversity. Baetidae, Nemouridae, and Chloroperlidae are likely to be the first mayfly and stonefly taxa to colonize glacier-fed rivers, but Diamesinae and Orthocladiinae typically remain numerically dominant in the community (Milner and Petts 1994).

Severe disturbances generated by volcanic eruptions, such as complete channel filling, water temperature increases above the boiling point, and complete denuding of riparian areas, lead to recovery through primary succession at affected sites. In the Drift River, which has a watershed that is fed by numerous glaciers, one would expect to find a macroinvertebrate community similar to that in other nearby glacier-fed rivers, except for the severe habitat-altering effects that may be attributed to the most recent eruptions of Redoubt Volcano. This study, done in June 1995, examined the macroinvertebrate community structure of the Drift River about five years after the last 1989–1990 eruption ended. The objectives of this study were to: (1) determine the abundance and the community composition and structure of macroinvertebrates in the Drift River, (2) evaluate the recovery of the Drift River by comparing its macroinvertebrate abundance and its community composition and structure with those in similar nearby streams not directly affected by the most recent volcanic activity at Redoubt Volcano, and (3) evaluate salmonid habitat implication in the Drift River and at other streams draining recently active volcanoes in the Cook Inlet region.

Description of the Study Area

Macroinvertebrate samples were collected in 1995 from three streams: the Drift River, which drains Redoubt Volcano; the Johnson River, which drains Iliamna Volcano; and Cannery Creek, which drains foothills near Redoubt Volcano. The Johnson River and Cannery Creek were used as reference sites, representing unstressed (by recent volcanic activity) systems with which to compare the Drift River.

The Drift River originates in the Chigmit Mountains (Figure 1) and flows eastward about 60 km before entering Cook Inlet. Approximately 40 km of the Drift River is downstream from Redoubt Volcano (Figure 2). Volcanic debris flows, large floods, and pyroclastic flows associated with the 1989–1990 eruption primarily traveled downstream to the east. Upstream from the Drift River lobe of Double Glacier (Figure 2), the Drift River Valley is about 1.5 km wide and is confined between steep canyon walls approximately 1000 m high; downstream from this lobe, the valley gradually broadens out

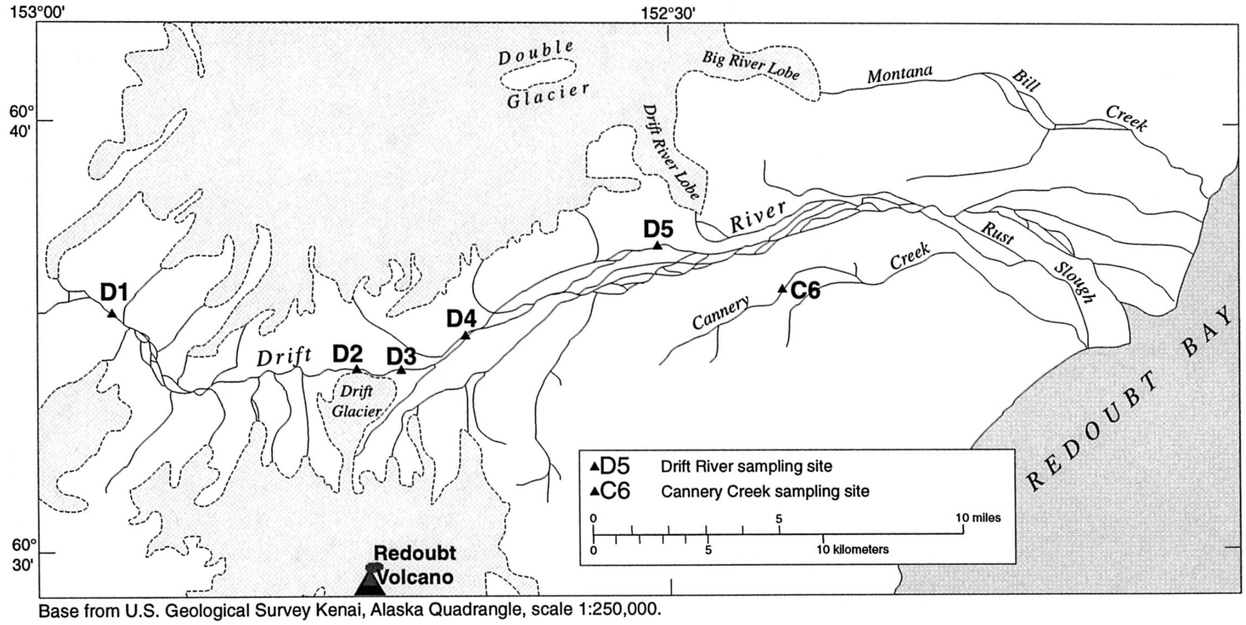


Figure 2. Location of macroinvertebrate sampling sites along the Drift River and Cannery Creek near Redoubt Volcano.

into an alluvial fan more than 10 km wide. The total drainage area of the Drift River is about 570 km^2, of which 240 km^2 (42%) is covered by glaciers. The drainage area upstream from Redoubt Volcano is 250 km^2 and was generally unaffected by the 1989–1990 eruption. Flow in the river is normally dominated by snowmelt runoff and seasonal glacier melting. During the summer, mean flow is about 50 to 80 m^3/sec (Dorava and Meyer 1994). The mean basin altitude is 980 m, and the annual rain and snowfall total about 3200 mm.

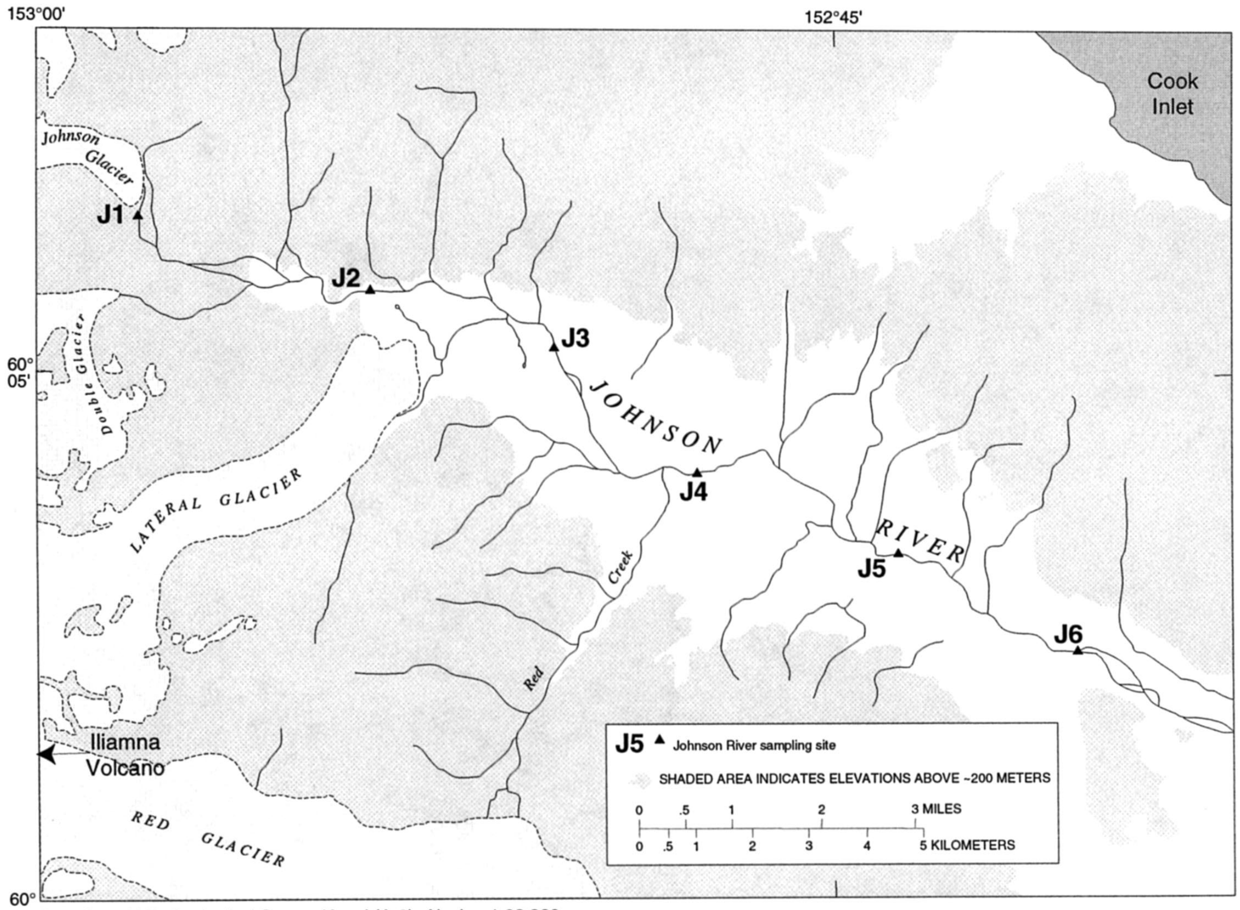
The Johnson River (Figure 3) drains an area of about 150 km^2 bounded on the north by Tuxedni Bay and to the south by Chinitna Bay between the Aleutian Range and Cook Inlet (Figure 1). The headwaters of the Johnson River form near the terminus of the Johnson Glacier (Figure 3) at an altitude of about 165 m. The river is approximately 26 km long and flows through a broad U-shaped valley typical of many glacier-fed rivers in Alaska. Glacier meltwater also enters the upper valley from the Double and Lateral glaciers (Figure 3). The upper 8 km of the Johnson River flows across unconsolidated glacial and fluvial deposits, which are covered with extensive alder thickets. The lower 3 km of the river is braided. Although no stream-gauging station was on the river at the time of the study, it is estimated that peak discharge in the summer probably ranges from 60 to 85 m^3/sec (Timothy Brabets, US Geological Survey, written communication 1996).

The Johnson River was selected to provide samples of an undisturbed macroinvertebrate community. This glacier-fed river has not been directly affected by volcanic activity during the last 10,000 years. The most recent significant nonvolcanic physical disturbances are associated with a landslide and debris avalanche that traveled the length of the river at least 300 years ago (Jim Begét, University of Alaska Fairbanks, oral communication 1996).

Cannery Creek (Figure 2) is also predominantly fed by glacier meltwater, but its drainage area of 50 km^2 is smaller than those of the Drift and Johnson rivers. The macroinvertebrate sampling site in Cannery Creek was upstream from the area directly affected by flows induced by the 1989–1990 eruption of Redoubt Volcano.

Volcanic Disturbances in the Drift River

Adjustment of a river's morphology to massive additions of sediment, such as those resulting from volcanic eruptions, may take several years (Meyer and Martinson 1989). Following the 1989–1990 eruptions of Redoubt Volcano, repetitive, monumented channel cross-section surveys were used to document scour and deposition along the Drift River. A summary of the initial adjustments occurring during the spring and summer of 1990 are discussed here. Additional details can be found in Dorava and others (1993). Initially, several meters of frozen unconsolidated sediment was deposited in the first few kilometers downstream from Drift Glacier by



Base from U.S. Geological Survey Kenai (A-8), Alaska, 1:63,360

Figure 3. Location of macroinvertebrate sampling sites along the Johnson River near Iliamna Volcano, Alaska.

volcanogenic flows during the December 1989 eruption (Trabant and others 1994). Subsequently, massive debris flows added as much as 10 m of sediment to the river channels. After several months, the channels in the upper river commonly scoured back down to within a meter of the predeposition elevation (Dorava and others 1993), whereas sediment deposits 1–5 m thick still remain on the flood plain and alluvial fan.

Deposition of sediment by lahars and lahar-runout flows caused the lower Drift River to be diverted southward into Rust Slough and into the lower reach of Cannery Creek (Figure 2). Between 15 February and 26 May 1990, lahars eroded the upper part of the Drift River valley. During an 18-month period following the 15 February eruption, more than 2×10^6 m^3 of material per kilometer was removed from the first 30 km of the Drift River valley downstream from Redoubt Volcano (Dorava 1992). Aggradation of the channel bed downstream caused Rust Slough and Cannery Creek to overflow their banks. Because Rust Slough and Cannery Creek could not accommodate the subsequent flows, their channels moved northward to the Drift River valley (Dorava and Meyer 1994). Then, the Drift River channel also migrated northward and a new channel was cut through the north bank of the Drift River. This northward channel migration caused some water from the Drift River to flow into the headwaters of Montana Bill Creek (Figure 2). Subsequently, flow down the main channel of Montana Bill Creek was increased: since about August 1990, between 40% and 60% of the Drift River flow has been down the channel of this creek.

Extensive areas of the riparian zone in the lower Drift River valley were covered with mature black spruce, cottonwood, and willow before the 1989–1990 eruptions. Many of these areas were buried or destroyed by fast-moving lahars. A mature black spruce forest, several square kilometers in size, near the mouth of the Drift River was destroyed and most trees growing adjacent to the Drift River were removed. It is likely that similar disturbances of the Drift River occurred during previous eruptions in 1902 and in 1966–1968. Inundation of the Drift River Valley during the 24 January 1966 eruption (Post and Mayo 1971) was similar to the one that occurred during the 15 December 1989 eruption (Dorava and Meyer 1994).

The documented fluvial geomorphic changes along the lower Drift River demonstrate the dynamic nature of river channels when large quantities of water and sediment are added to them. Physical alterations to the aquatic habitat in the Drift River have been severe and have occurred relatively frequently: three eruptions of similar size have occurred during the last 95 years. Although the peak discharge and sediment loads of the 1902 and 1966–1968 eruption-induced flows on the Drift River are not precisely known, volcanogenic flows during the 1989–1990 eruptions were at least 100 times larger than those estimated for a 100-year meteorologically generated flood (Dorava and Meyer 1994). The channel changes that occurred in the 40-km-long reach of the Drift River downstream from Redoubt Volcano are examples of the types of effects that may result from volcanic eruptions in similar settings (Dorava and others 1993).

Methods

Six macroinvertebrate sampling sites were established along the Drift River and nearby glacier-fed Cannery Creek (Figure 2) in early June 1995. The sites selected were predominantly riffle areas that typically provide the best available macroinvertebrate habitat. Two sites were not significantly affected by the 1989–1990 eruptions of Redoubt Volcano: one site in the headwaters of the Drift River (D1) and one in the headwaters of Cannery Creek (C6). The sites were sampled using a modified Surber sampler in the wadable reaches of streams according to methods described by Britton and Greeson (1987) and Milner and Oswood (1991). A total of 26 macroinvertebrate samples were collected with the Surber sampler, which had an average sampling area of about 0.30 m^2. Five replicate samples were collected at sites D1, D3, D4, and D5; two at site D2; and four at site C6. Turbidity, water temperature, and specific conductance were measured at each site, and water depth, current velocity, and predominant substrate size were recorded for each sample. Macroinvertebrates were preserved in 90% ethanol, sorted in the laboratory, and identified to genus for most taxa and to family and subfamily for the Diptera. A set of voucher specimens is stored at the Institute of Arctic Biology, University of Alaska, Fairbanks, where the identifications were made.

Three replicate Surber samples of macroinvertebrates were collected at six sites along the Johnson River (Figure 3). In addition, water-quality properties were measured and physical characteristics were recorded at each sampling site along the Johnson River as were done on the Drift River.

Recovery of the macroinvertebrate community in the Drift River was evaluated by comparing samples collected from sites downstream from Redoubt Volcano with those from the Johnson River, Cannery Creek, and the undisturbed site on the Drift River. Additional analyses were made with the predictive model of Milner and Petts (1994) to determine if Drift River macroinvertebrate communities are similar to those in other glacier-fed rivers. Intersite comparisons were made by computing a Jaccard's community coefficient (C_j) (Gore 1985, Klemm and others 1990). This coefficient measures the degree of similarity in taxonomic composition between two samples in terms of taxa presence or absence (Gore 1985, Klemm and others 1990). In our analysis, a minimum of three individuals of a particular species had to be found at a sampling site for inclusion in the coefficient calculation.

An assessment of the salmonid habitat recovery was made by evaluating the magnitude of physical disturbances along the Drift River. The implication for aquatic habitat loss and subsequent recovery or restoration at similar rivers in the Cook Inlet region is described in terms of the economic value of the Cook Inlet salmon fishery, the frequency of eruptions at regional volcanoes, and the extent of aquatic habitat surrounding these volcanoes.

Results

Of the Drift River sites, the density of macroinvertebrates and the number of taxa were lowest at sites D2 and D3 (Table 1). Because these two sites were the ones closest to Redoubt Volcano (Figure 2) and also closest to Drift Glacier, they may demonstrate the effects of both the 1989–1990 eruption and the glacier. The number of macroinvertebrates at the other sites was relatively high for a glacier-fed river in southcentral Alaska. For example, mean density for the remaining three Drift River sites averaged about 870 / m^2 and site D4 had a mean density that exceeded 1000 / m^2.

The percentages of Diptera, Ephemeroptera, and Plecoptera were compared for selected sites (Figure 4). Site D1 upstream from Drift Glacier and Redoubt Volcano and site D3 downstream from Drift Glacier and Redoubt Volcano each had a higher percentage of Ephemeroptera than Diptera, closely resembling the taxonomic mixture of typical south-central Alaska rivers (Oswood and others 1995). Site C6 on Cannery Creek also supported more Ephemeroptera than Diptera. Chironomids and the mayfly *Baetis* were present at all sites, because they are well adapted to glacier-fed rivers and are good pioneer taxa (Allan 1975). Milner and Petts (1994) specifically identified chironomids of the subfamilies Diamesinae and Orthocladiinae as consistently dominant in glacier-fed rivers. The absence of Trichoptera in all the Drift River samples is predicted by the qualitative model of Milner and Petts (1994), which describes the infrequent occurrence of Trichoptera in glacier-fed rivers because they are not specifically adapted to low temperatures and high streambed mobility.

Most of the chironomids in the Drift River probably belonged to the subfamily Diamesinae as predicted by the qualitative model of Milner and Petts (1994), but this cannot be verified without head mounts. Chironomids from Cannery Creek principally belonged to the subfamily Orthocladiinae. Overall, five stonefly taxa were collected: the most dominant was a Chloroperlidae stonefly, *Plumiperla,* except in Cannery Creek where *Podmosta* was dominant. Representatives of the families Nemouridae, Taeniopterygidae, and Capniidae were also found in small numbers. The macroinvertebrate community structure in the Drift River generally conforms with the qualitative model of Milner and Petts (1994), indicating that the river is presently supporting the macroinvertebrate community expected in a glacier-fed river. The one taxon absent that would be predicted by the model was Simuliidae (blackflies).

The macroinvertebrate taxa found at the six mainstem Johnson River sites (Figure 3, Table 2) also correspond well with the qualitative model of Milner and Petts (1994). Because channel stability did not appear to increase dramatically in the downstream direction, macroinvertebrate community diversity remained low in the downstream reaches of the Johnson River. The fauna was characterized by three main taxa: *Baetis,* a mayfly; *Plumiperla,* a Chloroperlidae stonefly; and chironomids, principally of the subfamily Diamesinae. An additional mayfly genus, *Cinygmula,* was found at sites J4, J5, and J6, and Simuliidae were found at site J6. Densities at the six Johnson River sites averaged about 460/m^2: the lowest was 284/m^2 at site J3 and the highest was 710/m^2 at site J5 (Table 2). Using a Mann-Whitney test at a significance level of 0.05, these densities are not significantly different from those in the Drift River (Zar 1984).

To evaluate recovery of the recently disturbed Drift River sites, we compared the similarity of the macroinvertebrate community in undisturbed areas of the Drift River with the community in nearby similar streams. Jaccard's coefficient of community (C_j) was calculated using comparison sites D3, D4, and D5 along the lower Drift River, and reference sites D1 along the upper Drift River, C6 in nearby Cannery Creek, and J3 along the Johnson River (Table 3).

Site J3 on the Johnson River showed the greatest similarity to comparison sites on the Drift River. Reference site C6 on Cannery Creek was the least similar to the Drift River comparison sites. These results indicate that the greatest similarity was found from taxonomic comparison between the Drift River and the Johnson River, followed by comparisons between sites along the Drift River. The naturally depauperate macroinvertebrate communities in glacier-fed rivers provide relatively low numbers of taxa with low diversity, which skew these similarity comparisons. For example, between sites D1 and D3, where the similarity coefficient was 0.5, only one taxon was not common to both sites. The results also indicate that the comparisons between Cannery Creek and the Drift River were problematic. The low similarity in these taxonomic comparisons may result because the stream environments are different. Although both streams are predominantly glacier fed, the Cannery Creek sampling site had lower turbidity and lower water temperature than sampling sites D3, D4, and D5 (Table 1).

Discussion

The Drift River macroinvertebrate community is recovering five years after volcanic-induced disturbances of the aquatic habitat. This recovery is indicated by the following observations: (1) a relatively high density of macroinvertebrates was found in the river, (2) the macroinvertebrate taxa found were those expected in a glacier-fed river, and (3) the macroinvertebrate community composition and structure were similar to those in nearby undisturbed sites. However, these facts do not provide enough information to confirm full recovery. Without preeruption data, it is difficult to separate the effects of the 1989–1990 eruption of Redoubt Volcano from the effects of the proximity of sampling sites to the Drift Glacier. Verifying that a truly stable macroinvertebrate community presently exists downstream from Redoubt Volcano would require collecting additional macroinvertebrate samples.

The effects of the riverine environment on the macroinvertebrate community composition must be considered to evaluate and separate the effects of the recent eruption. The environmental effects can be assessed by examining the relation between environmental factors such as stream depth, velocity, temperature, turbidity, and substrate size and the mean density of macroinvertebrates found at a sampling site (Table 1). Although limited by the low number of samples collected, analysis of these relations indicated that water

Table 1. Drift River study site measurements and macroinvertebrate sample taxonomic composition and density[a]

	D1						D2			D3					
Water temperature (°C)	2.7						2.4			4.4					
Specific conductance (μs/cm)	25.9						100.8			54					
Turbidity (NTU)	38.2						41.5			42.9					
Predominant substrate size (cm)	5–15						100–150			50–200					
	Sample density						Sample density			Sample density					
	B1	B2	B3	B4	B5	Mean density	B1	B2	Mean density	B1	B2	B3	B4	B5	Mean density
Flow (cm/s)	80	80	50	90	120					50	60	50	70	50	
Depth (cm)	30	30	20	20	30					20	20	10	10	20	
Ephemeroptera															
Baetidae															
Baetis	43	13	204	527	731	303		54	27	75	86	11	312	65	110
Heptageniidae															
Eperorous				11		2									
Cinygmula			11			2									
Plecoptera															
Chloroperlidae															
Plumiperla			108	108	65	56									
Nemouridae															
Zapada				11		2							65		13
Podmosta								11	5						
Taeniopterygidae															
Taenionema															
Capniidae															
Diptera															
Chironomidae	118	205	172	215	570	256	11	97	59	32	129	65	118	22	73
Empididae					11	2									
Simulidae															
Tipulidae															
Olicochaeta															
Olicochaeta															
Total						623			91						196

Density for each taxa is presented for each sample and the mean of all samples at a site, in number per square meter.

[a]All sites sampled 9 June 1995.

temperature had the highest correlation with mean density of macroinvertebrates (Figure 5). The correlation coefficient for this relation is about 0.73, whereas the other environmental factors considered had a correlation coefficient of less than 0.50.

The high correlation between water temperature and the number of macroinvertebrates found at a site is clearly predicted by the model of Milner and Petts (1994). Additionally, the low correlation between the other measured environmental factors indicated that they may not significantly influence the number of macroinvertebrates found at a site. This evaluation reinforces the determination that the macroinvertebrate community downstream from Redoubt Volcano is recovering and that the variation in macroinvertebrate numbers found is not simply a function of the variation in environmental factors among the sites.

The recovery of the macroinvertebrate community in the Drift River was likely enhanced because the areas upstream from the volcano were unaffected by the eruptions and thus provided a source of drifting organisms to disturbed downstream areas. Where drift is present, recovery tends to be more rapid than when recolonization has to rely on aerial sources (Milner 1994). Another factor in the recovery is that the typical invertebrate community of a glacier-fed river has taxa that are specifically adapted to harsher environmental conditions associated with frequent disturbances and stresses. Thus, these taxa would likely begin to respond rapidly to a major volcanic disturbance.

Because few data are available describing the effects of volcanogenic disturbances on biological communities, comparing the recovery of macroinvertebrates in the Drift River with that of another eruption-affected river might be of interest. The recovery of macroinvertebrates in streams draining Mount St. Helens—such as

Table 1. (Continued)

D4						D5						C6 (Cannery Creek)				
5.7						6.6						3.6				
83						94.6						27.7				
39.8						26.3						25.8				
20–150 Sample density						20–150 Sample density						50–150 Sample density				
B1	B2	B3	B4	B5	Mean density	B1	B2	B3	B4	B5	Mean density	B1	B2	B3	B4	Mean density
60	70	80	60	70		20	40	50	50	50		80	80	80	80	
10	10	10	10	10		10	20	10	10	10		20	20	20	20	
441	334	603	1033	172	516	139	65	65	280	43	118	409	409	140	194	288
11	11		75	32	26	32	11			11	11					
												22	22	11		14
		43	11		11											
		11	11		4											
549	559	473	1044	334	592	1098	829	269	1356	538	818	344	463	22	118	237
												11	11			6
													11			3
					1041						947					548

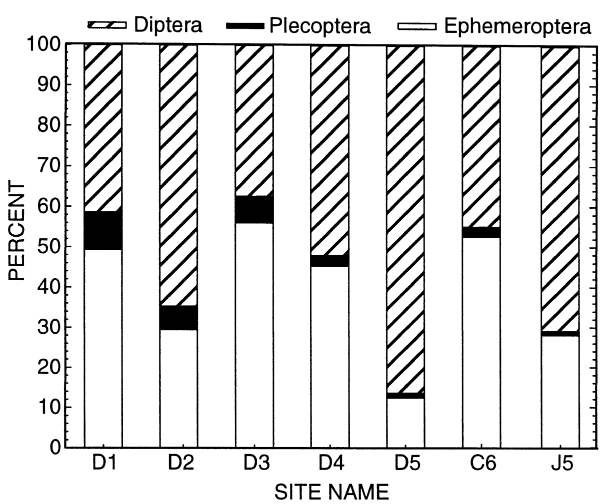


Figure 4. Percentage of Diptera, Plecoptera, and Ephemeroptera at the Drift River (D1–D5) and Cannery Creek (C6) sites, and the reference site on the Johnson River (J5).

Clearwater Creek, which was denuded of all macroinvertebrate fauna during the May 1980 eruption—began rapidly but took place over a lengthy time span. During 1980, 18 macroinvertebrate taxa recolonized Clearwater Creek, and by 1989, the number had increased to 80 (Meyerhoff 1991). The numerical dominance of chironomids decreased significantly from 75% in 1980 to 30% in 1989. Approximately nine years after the Mount St. Helens eruption, the ratio of Diptera (an order whose taxa are highly tolerant of disturbances) to Ephemeroptera, Plecoptera, and Trichoptera (orders whose taxa are much less tolerant of disturbances) was 0.3:1. In comparison, five years after the 1989–1990 Redoubt eruption, the same taxa ratio was 1.85:1 at site D2, 0.6:1 at site D3, 1.1:1 at site D4, and 6.44:1 at site D5. Although both systems were disturbed through volcanic activity, comparing the recovery of the Drift River to that of Clearwater Creek is somewhat problematic. Clearwater Creek is a nonturbid stream that is not fed by glaciers. Hence, the physical–chemical factors that

Table 2. Johnson River study site measurements and macroinvertebrate taxonomic composition and density[a]

	J1				J2				J3			
Water temperature (°C)		0.9				3.2				6.5		
Specific conductance (μs/cm)		22				44				110		
Turbidity (NTU)		42				18.2				38.4		
Predominant substrate size (cm)		10–15				8–12				12–16		
	Sample density			Mean density	Sample density			Mean density	Sample density			Mean density
	1	2	3		1	2	3		1	2	3	
Flow (cm/s)	50	75	71.2		125	94	121		80	102	97	
Depth (cm)	17	23	18.3		24	15	83		18	24	18	
Ephemeroptera												
Baetidae												
Baetis		11	54	22	11	11		7	32	140	54	75
Heptageniidae												
Cinygmula												
Plecoptera												
Chloroperlidae												
Plumiperla						43		14		11		4
Perlodidae												
Isoperla												
Trichoptera												
Rhyacophilidae												
Rhyacophila		11	11	7								
Diptera												
Chironomidae	140	215	474	276	893	280	226	466	194	236	183	205
Empididae	11			4								
Simulidae												
Total				309				487				284

Density for each taxa is presented for each sample and the mean of all samples at a site, in number per square meter.

[a]J1 and J2 were sampled 23 June 1995; J3–J6, 24 June 1995.

naturally limit macroinvertebrate diversity and abundance in glacier-fed systems (low temperatures and channel instability) do not restrict colonization by other taxa to the same extent in Clearwater Creek. Furthermore, the comparison of these two streams is complicated because a source of upstream organisms was probably not available in Clearwater Creek to enhance colonization by drift as was available in the Drift River.

Although specific information is not available about the salmonid fish population in the Drift River, it is likely that their populations were seriously affected by the recent eruption of Redoubt Volcano. Fish access to the river was altered by large channel changes, spawning sites were destroyed or modified by thick deposits of fine sediment, and food sources for rearing fish were reduced or eliminated. Most of the riparian zone vegetation was removed or killed by the lahars. These eruption-induced changes altered primary production by substantially decreasing allochthonous energy input from the riparian areas. Subsequently, secondary production was most likely reduced by this decrease in available energy.

When volcanic disturbance is considered in the context of the life history of a salmon, the initial consequence of the 1989–1990 eruption of Redoubt Volcano was an interruption of the rearing stage. Juvenile salmon in the Drift River were subjected to hot lahars that left deposits along the entire river at temperatures above the boiling point. If these hot lahars were somehow avoided, the juvenile salmon existed in a river with an extremely unstable channel devoid of riparian vegetation or they were prematurely washed out to the ocean. In subsequent years, returning salmon found migratory impediments formed by lahar deposits and channel head-cutting near the mouth of the river. If returning salmon were able to enter the river, coarse gravels used for spawning were covered by lahar deposits or the streambeds were very unstable. The effect of the substantial loss of a single year's juvenile salmon population may not be evident until these salmon return to the river to spawn in four or five years. Reductions in salmon production during subsequent years may continue until the physical alterations recover, and it may take decades for mature spruce to

Table 2. (Continued)

J4				J5				J6			
3.2@1000 6.7@1500				7.8				3.5@0900 8.2@1500			
140								130			
29.4				31.9				36.2			
8–14 Sample density				10–14 Sample density				8–12 Sample density			
1	2	3	Mean density	1	2	3	Mean density	1	2	3	Mean density
73	94	79						100	76	137	
12	15	9						21	6	15	
86	86	301	158	215	258	118	197	32	139	43	72
	11		4	11			4	11	11		7
32		11	14		11	11	7				
										11	4
215	334	258	269	387	657	463	502	280	646	355	427
								11			4
			445				710				514

Table 3. Value of Jaccard's coefficients of community for the Drift River sites

	Similarity coefficient (C_j) at reference site		
Comparison site	D1	C6	J3
D3	0.50	0.50	1.00
D4	0.75	0.40	0.75
D5	1.00	0.50	1.00

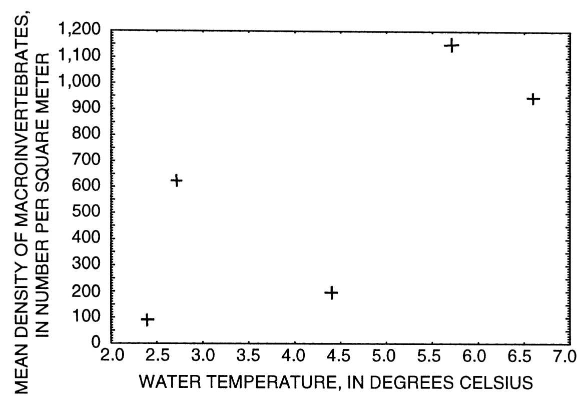


Figure 5. Mean macroinvertebrate density in the Drift River as a function of water temperature.

return to damaged riparian areas. Measurements of the health of the macroinvertebrate community, as indicated by their abundance and diversity, provide information about potential recovery of the salmon population. This relation results because the macroinvertebrates are a primary food source of juvenile salmon. In addition, because macroinvertebrates integrate water-quality and habitat characteristics over their life cycle of a few months, they are more indicative of recent disturbances than salmon, whose life cycle can extend over several years.

Regional Volcanic Activity and Implication for Recovery or Restoration

During the past 10,000 years, numerous volcanoes have erupted in the Cook Inlet region (Riehle 1985). The effects on aquatic habitat associated with these previous Cook Inlet region volcano eruptions provide examples of what might be anticipated with future eruptions. Observations at these and other volcanoes in the United States indicate that physical, biological, and chemical changes resulting from even modest eruptions can be extreme. Additionally, many areas near Alaskan volcanoes are uninhabited, and the principal environmental effects occur in areas that are important fish and wildlife habitat. Because of the economic importance of the Cook Inlet region fisheries, it must be asked whether restoration of streams affected by volcanic eruptions is a viable proposition. Furthermore, when considering the potential effects of future eruptions, it is important to evaluate the magnitude and frequency of eruptions at a specific volcano and the location of the volcano in relation to salmonid fish streams. The eruptive history at each volcano in the Cook Inlet region and some information about fish habitat in watersheds near the volcanoes are provided in Table 4.

Although Augustine Volcano has had only seven to ten eruptions during the past 10,000 years, six of these have occurred in the last 200 years, making Augustine the most active volcano in the Cook Inlet region during historical time. However, because Augustine Volcano is on a small island with no permanent streams, little fish habitat—other than some near-shore migratory routes—would likely be affected by an eruption. At Iliamna Volcano, the situation is much different. The eruptive history indicates only one previous eruption (Wood and Kienle 1990), but the volcano is surrounded by extremely productive fish habitat (Alaska Department of Fish and Game, written communication 1993, Russell and National Park Service 1980). For Redoubt and Spurr volcanoes, the eruptive history and fish habitat resources are similar to each other. Both volcanoes have been active recently and frequently during the past 10,000 years. Streams close to and draining these volcanoes provide important salmon migrating, spawning, and rearing habitats (Alaska Department of Fish and Game, written communication 1993, Russell and National Park Service 1980). One distinction between these two volcanoes may be that the magnitude of recent eruptions appears to be greater at Redoubt than at Spurr (Miller and Chouet 1994, Keith 1995). At Hayes Volcano, in spite of the lack of recent activity, there is cause for concern about future eruptions because of the great length of anadromous fish streams downstream from the volcano. The Skwentna, Yentna, and Susitna rivers downstream from Hayes Volcano (Figure 1) provide important commercial, sport, and subsistence fisheries.

A relative ranking system of Cook Inlet region volcanoes was constructed using the history of eruptive activity at each volcano and the extent of fish habitats

Table 4. Volcano eruptive history and salmonid fish habitats in the Cook Inlet region

Volcano (Figure 1)	Number of known eruptions in the last 10,000 years	Last known eruption date	Approxmate stream distance to the coast (km)	Known fishery habitat in local streams[a]
Augustine	7–10	1986	8	M
Iliamna	1	Unknown	30	M, S, R
Redoubt	30	1990	40	M, S, R
Spurr	35	1992	50	M, S, R
Hayes	6	3500 yr BP	200	M, S, R

[a]M, migratory; S, spawning; R, rearing.

Table 5. Relative ranking of Cook Inlet region volcanoes based on eruption history and extent of fish habitat

Volcano (Figure 1)	Eruption history	Extent of fish habitat downstream
Augustine	1	5
Spurr	2	3
Redoubt	3	4
Hayes	4	1
Iliamna	5	2

downstream from each volcano (Table 5). This ranking system combines the likelihood of future eruptions with the potential loss of fish habitat. The ranking scheme indicates that the most likely volcano to erupt (Augustine) will affect the area of least fish habitat and that the area of most fish habitat is downstream from the volcano with the second lowest likelihood to erupt (Hayes) (Table 5).

Following recent volcano eruptions at Redoubt and Spurr volcanoes, aquatic habitat has been adversely affected in streams that became blocked with sediment. This sediment influx caused rapid changes in streambed elevation, extensive flooding, channel migration, and considerable destruction of riparian vegetation. These physical alterations affect both macroinvertebrate and salmonid communities and are likely to persist for years. In the sections of the Drift River upstream from the alluvial fan, the macroinvertebrate community appears to be recovering five years after the most recent eruption. However, the channel of the Drift River downstream from the apex of the alluvial fan remains very unstable. The 0.5 to 1.0-m-high near-vertical banks have no vegetation and appear unstable, as shown by numerous fresh slumps of bank material present during June 1995. A large quantity of sediment was delivered to this lower section of the river by the 1989–1990 lahars (Dorava 1992). The downstream movement of large volumes of sediment in the alluvial fan of the Drift River will likely continue for some time.

No information is available to compare the pre- and posteruption populations of salmon in the Drift River. Recreational sport-fishing sites along the Drift River had to be relocated because of the substantial channel modifications. The number of salmon caught by local set-net fishermen near the mouth of the Drift River decreased after the 1989–1990 eruptions (Ron Green, Drift River Oil Terminal, oral communication 1996). The presence of the expected types and numbers of macroinvertebrates in the Drift River indicates that their habitat is returning to preeruption conditions. However, the habitat characteristics suitable for salmonids are different from those required by macroinvertebrates. Recovery from the physical alterations to the river channel and the regrowth of the riparian vegetation likely will take longer than recolonization by macroinvertebrates. Without specific pre- and posteruption population information on the fishery, only speculation about disturbance to, or the recovery of, the fishery is possible. However, it is certain that the physical alterations to the Drift River—including the in-filling of the river channel and deposition in the riparian areas resulting from the 1989–1990 eruptions—were detrimental to the fishery. Salmon depend on freshwater environments to propagate and some species, such as chinook (*Oncorhynchus tshawytscha*), rear in their natal rivers for more than a year (Healey 1991). While rearing in freshwater, juvenile chinook salmon prefer cool, clear, slow-moving water and feed primarily on larval and adult insects (Healey 1991). In Alaska, these preferred habitat characteristics are commonly found in forested rivers that drain the coastal mountains. In places where these rivers are located near with active volcanoes, recurrent eruption-induced disturbances have adversely affected the available fish habitat.

The loss of aquatic resources associated with volcanic activity in the Cook Inlet region has not been adequately quantified. Most of the sport fishing in the Cook Inlet area is concentrated in the Kenai River, about 100 km east of Redoubt Volcano (Mills 1994). The Kenai River commercial and sport fisheries has contributed as much as $78 million annually to the state's economy (Liepitz 1994). As salmon populations are reduced in the Pacific Northwest and elsewhere in Alaska, more economic importance will be placed on smaller fisheries.

When the North American Pacific salmon resource reaches a threshold condition in which all anadromous fish rivers are critical, an essential issue will be whether or not restoration of these volcanically disturbed aquatic systems is feasible or economically viable. Regrowth of the mature spruce forest in the lower Drift River valley will take decades, and removal of the sediment deposited along the lower reaches of the Drift River would be extremely costly and time consuming. A complete restoration project in a drainage basin affected by an eruption could be very expensive and lengthy. Sediment retention structures built along the Toutle River following the 1980 eruption of Mount St. Helens took years to complete and cost millions of dollars (Franklin and others 1988). Additionally, 26 million seedlings were planted near Mount St. Helens to assist revegetation of affected lands and more than 400,000 steelhead trout were planted in area rivers to assist recovery of the fishery (Franklin and others 1988). Natural recovery of eruption-disturbed basins may be a more practical alternative; however, the rates of total river (aquatic and riparian habitat) recovery are unknown, but most likely are lengthy. The macroinvertebrate community in the Drift River appears to be recovering five years after the 1989–1990 Redoubt Volcano eruption. This recovery process is most likely enhanced because undisturbed upstream areas supplied colonizing taxa, and the taxa of glacier-fed rivers are especially adapted to disturbances. However, the recovery of physical disturbances—such as the anadromous fish migration routes, spawning and rearing habitats, and riparian areas—damaged during these eruptions, is anticipated to be substantially longer. Additionally, physical disturbances of the type described may be so frequent in drainage basins near Cook Inlet region volcanoes that they interrupt the lengthy recovery process.

The importance of the Drift River, the Johnson River, or other rivers near volcanoes to the overall vitality of the Cook Inlet salmon population is not known. However, at some point in the future, the health of all rivers that support anadromous fish in the region will become critical because of the cumulative adverse effects of volcanism, development, fish harvesting, and natural resource utilization. When that time comes, management strategies to mitigate for natural disturbances may be especially important. Understanding the frequency and magnitude of eruption-induced disturbances and the rate of natural recovery, will assist in developing these mitigation measures, if they are needed.

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