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Bull Trout Spawning Activity, Gold Creek, Washington

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Key Words

bull trout, Gold Creek, life-history requirements, spawning, precipitation, channel dewatering

Bull Trout Spawning Activity, Gold Creek, Washington

R.C. WISSMAR AND S. CRAIG

Abstract.—A high risk-remnant adfluvial bull trout *Salvelinus confluentus* population was studied during the spawning periods of 1993 and 1994 in Gold Creek in the Cascade Mountains, Washington. The objectives were to evaluate bull trout spawning activity, mortality rates, and influences of environmental factors (habitats, hydrology and temperature). Migrations of bull trout spawning populations during the summer and fall months were interrupted when the main channel became dry and impassable. A dewatered reach effectively isolated portions of the bull trout and other fish populations and allowed weekly snorkel estimates of the relative abundance of fish above and below the dewatered reach. Channel dewatering, caused by low rainfall, effectively fragmented the bull trout population and imposed spatial constraints on the distribution other fish (brook trout *S. fontinalis*, cutthrout *Oncorhynchus clarki*, kokanee *O. nerka*). Hydrological factors, specifically channel dewatering, represented the major factors controlling adult bull trout distribution and survival. The preferred habitats of spawning fish were shallow riffles and pools (<1.0 m in depth) in the upstream reaches. During 1993, there was a mortality of 63% relative to 24 spawning fish, and in 1994, a mortality of 24% relative to 29 fish. Bull trout experienced the lowest mortality during one month of channel dewatering and the highest during two months of dewatering. A retrospective analysis suggests that survival increases when recruits of mixed ages experience high survival rates during one to several previous spawning years. Conversely, during years when consecutive years of survival is low for mixed ages, additional sources of mortality and longer periods of dewatering could be devastating. Bull trout survival in Gold Creek not only appears related to rigorous environmental conditions during spawning, but to human modifications and genetic isolation. Bull trout were isolated by a dam in 1906. The isolation of this small population suggests the bull trout are at risk of impaired genetic fitness as a result of a limited gene pool.

INTRODUCTION

The spawning activity and migration of an isolated bull trout *Salvelinus confluentus* migration was documented during August to November 1993 and June to November 1994 in Gold Creek, Washington. Gold Creek originates in the Cascade Mountains and is a tributary to Keechelus Lake in the headwaters of the Yakima River, within the Columbia River Basin (Figure 1). The adfluvial bull trout population of Gold Creek is considered a high risk population (Mongillo 1992; WDW 1993). The study's objective was to evaluate bull trout spawning activity, mortality rates, and influences of environmental factors during the summer and fall. The environmental studies included monitoring habitat preferences of bull trout, habitat geomorphic conditions, streamflow and temperatures, and the presence of other coexisting fish populations.

Gold Creek maintains the only known spawning habitat for the adfluvial bull trout of Keechelus Lake (Washington Department of Fisheries and Wildlife, Olympia, pers. comm.). Bull trout were isolated in 1911 when the U.S. Bureau of Reclamation modified the original lake to a reservoir for irrigation and flood control purposes (Prater 1981).

STUDY AREA

Gold Creek is a third-order stream located near Snoqualmie Pass (86 km east of Seattle) on the east side of the Cascade Mountains (Figure 1). The climate of the Snoqualmie Pass area is influenced by elevation, terrain, and the prevailing winds. Annual total precipitation (4.2 km southeast of Gold Creek at Stampede Pass, elevation 1,207 m) averages 226 cm with snowfalls exceeding 1,120 cm. July and August are the driest months with precipitation commonly less than 6 cm. Mean air temperatures for November to early April range from -2.2° to 2.2°C and for July through September from 15.0° to 18.3°C, respectively.

Gold Creek's watershed (36-km^2 watershed) originates near Chikamin Ridge (elevation 2,111 m) and flows 13 km southwest before entering Keechelus Lake. Keechelus Lake was originally formed by a large residual moraine created from alpine glaciation. The lake's regulated water levels now range from highs at the Rocky Run Bridge near the Interstate 90 freeway (Figure 1) to the original pre-dam lake shoreline approximately 2.4 km below the bridge. At full storage, Keechelus Lake approaches 767 m above sea level, a maximum depth of 94 m, and a surface area of 10.5 km^2 (Dion 1978).

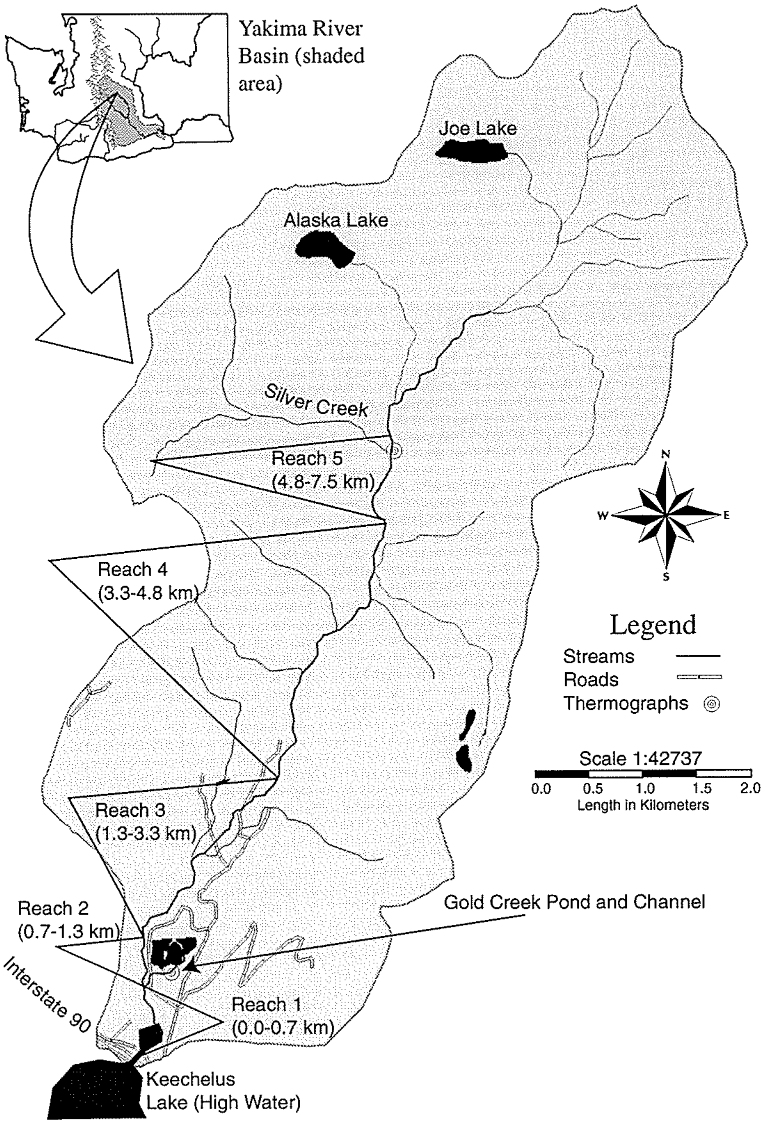

Figure 1. Location of Gold Creek, a tributary to Keechelus Lake in the headwaters of the Yakima River, Washington. Gold Creek originates on the eastern side of the Cascade Mountains.

The Gold Creek–Keechelus Lake catchment (142 km^2) is a U-shaped, glacially formed valley that contains alluvial and colluvial deposits that are highly permeable to groundwater flows. The basin lies northeast to southwest with three main tributaries that contribute more than 90% of the surface flow. The major upstream tributaries relative to the main channel (0 km at the Rocky Run Bridge) include the Gold Creek Pond outlet channel at 0.7 km, Silver Creek (7.3 km) and Alaska Creek (7.9 km) (Figure 1).

Historical discharge information is limited for Gold Creek (Prater 1981). Peak flows during late spring occur because of snow melt; however, major storm-induced floods can occur in late autumn and during the winter. A major rain-on-snow flood in November 1990 induced rainfalls of 4–10 cm d^{-1}. The 100-year flood event (Ketcheson 1992) changed the coarse of Gold Creek's main channel between 1.9–2.0 and 3.3–3.5 km.

The Snoqualmie Pass recreation area and the Gold Creek–Keechelus Lake catchment have been significantly modified from natural conditions. Historical changes in the landscape include mining and dam construction during the past 100 years. Since World War II, landscape changes in the area include the development of ski resorts, timber harvest activities, and construction of the interstate highway (Prater 1981). Major impacts to the Gold Creek watershed occurred when the Washington State Department of Transportation (DOT) added several lanes to the

Interstate 90 freeway near the stream's mouth (Figure 1). In addition to altering the channel, gravel required for highway construction was removed from a gravel pit in the Gold Creek floodplain. Gravel was excavated from approximately 0.09 km^2 of the alluvial flood plain to a depth of 14 m. Today, year-round groundwater inflows in the gravel pit form the Gold Creek Pond. An outlet channel that connects the pond to Gold Creek was constructed by DOT during gravel extraction. Restoration of the Gold Creek pond outlet by the Mt. Baker–Snoqualmie National Forest in 1992 included enhancement of spawning habitats for bull trout and kokanee salmon (*Oncorhynchus nerka*).

Bull trout, along with cutthroat trout *Oncorhynchus clarki* and mountain whitefish *Prosopium williamsoni*, probably colonized the Gold Creek–Keechelus Lake catchment prior to the arrival of anadromous salmon in the upper Yakima River basin (Meehan and Bjornn 1991). Adfluvial bull trout in Gold Creek probably coexist with other salmonid fish by occupying a different niche. Kokanee salmon, brook trout *S. fontinalis,* eelpout *Lota lota*, northern squawfish *Ptychocheilus oregonensis*, suckers *Catostomidae* sp., and chiselmouth *Acrocheilus alutaceus* (Wydoski and Whitney 1979) also utilize the lake and stream habitats of the catchment.

Mature fish that spawn in Gold Creek are from the 4- to 12-year class; they can return to spawn several times but generally not in successive years (Bjornn 1991). Bull trout commonly spawn between August and October when temperatures drop below 10°C (Bjornn 1991). Preferred habitats of juvenile bull trout most likely include cool waters (<15°C) of Gold Creek while adults reside in Keechelus Lake. Juvenile bull trout populations of Gold Creek probably rear from 1 to 4 years in the stream and then migrate to Keechelus Lake where they mature and take advantage of more diverse food supplies. Bull trout tend to be more piscivorous than other trout and salmon (Bjornn 1991). The most important forage resources for adult bull trout likely include juvenile kokanee salmon in Keechelus Lake. Such forage conditions also exist in Flathead Lake, Montana, and Priest Lake, Idaho (Bjornn and Reiser 1991). Similar life-history characteristics for adfluvial bull trout have been described (Fraley and Shepard 1989; Goetz 1989; Bjornn 1991; Reiman and McIntyre 1993).

METHODS

The speciation of adult bull trout in Gold Creek was examined using four adult carcasses ranging in size from 472 to 550 mm fork length. The speciation of *S. confluentus* relative to the Dolly Varden (*S. malma*) was verified using the Hass and McPhail (1991) linear discriminant function (LDF):

$$\mathrm{LDF} = .629\mathrm{BR} + .178\ \mathrm{AFR} + 37.100\ \mathrm{UJL/SL} - 21.800$$

where BR = the total branchiostagal rays,
AFR = total anal fin rays,
UJL = upper jaw length, and
SL = standard length.

The LDF averaged 1.6 (range 0.5–2.3), indicating all four fish were bull trout. However, the fish with an LDF of 0.5 suggested some characteristics of a reciprocal hybrid with brook trout. Adult bull trout identification was distinguished from brook trout by observing spots and the lack of vermiculations in the bull trout's body region. This was easily accomplished during the surveys owing to the docile actions of the adult bull trout.

Bull trout spawning activity and mortality, and stream habitat and physical characteristics were investigated within five reaches of the main channel and the Gold Creek Pond outlet. Reach 1, the most downstream reach (0–0.7 km; mean channel gradient 0.7%), begins at the high water mark of Keechelus Lake (0 km at the Rocky Run Bridge) and extends upstream to the confluence with the Gold Creek outlet at 0.7 km (Figure 1). The Gold Creek Pond outlet connects the pond to the main channel (length 560 m, mean channel gradient 0.7%). Reach 2 begins at the main channel confluence with the pond outlet and extends upstream to 1.3 km. This reach dewaters during rainless periods (mean channel gradient of 1.0%). Reach 3 (1.3–3.3 km) exhibits a slight increase in mean channel gradient (1.6%), downwelling areas, and fluctuating water levels during rainless periods. Reach 4 (3.3–4.8 km) can also contain downwelling areas during rainless periods (mean channel gradient 2.4%). The upstream channel shows a distinct gradient break (2.5%) with reach 5 and becomes a major fish migration barrier during low stream flows (July to October). Reach 5 extends from 4.8 to 7.5 km with a channel gradient of 2.5%. Channel gradients upstream of reach 5 range from 1% to 6% with high gradients forming migration barriers.

Descriptions of channel geomorphic conditions and habitats are from 1992 and 1993 summer survey data of the Mt. Baker–Snoqualmie National Forest. The survey method, a visual estimation technique for measuring channel habitat units, was adapted from Hankin and Reeves (1988) with microhabitat descriptions from Bisson et al. (1982). Habitat categories for main and side channel units include riffles, pools, and glides. The side channels included all braided channels.

Large woody debris (LWD, dia. >30 cm and length >10 m) was enumerated relative to the active channel width. Dominant and sub-dominant streambed substrate was visually estimated for each habitat unit (n = 255) within the following size categories (mean diameter): sand smaller than 2 mm; gravel 2–65 mm; cobble 65–254 mm; and boulders larger than 254 mm.

Weekly surveys of fish abundance and spawning activity were conducted by snorkeling and streamside observations. Spawning locations were defined as redds with well-defined tailout sections and adequate protection for the eggs from flow and predation. Test digs or probable redds (Weaver and Fraley 1991) were considered as areas showing fish digging activity but without tailout areas capable of covering eggs. No attempts were made to uncover the eggs because of the population's high-risk status. After a spawning site was located the habitat type was recorded from the stream survey.

Spawning-site measurements included wetted and bankfull stream widths (Hankin and Reeves 1988), redd/test dig dimensions (redd/test surface area from total length and average width of disturbed area), pebble counts (Wolman 1954), tailout depth, distance and depth to the nearest associated cover, depths greater than 0.2 m of turbulence, and crevasses and debris associated with the disturbed area. Tailout depth was considered the minimum depth associated with the disturbed areas of tailspill. Cover was determined by the ability for spawners to conceal themselves from predators. Spherical densiometer readings of percent riparian canopy density (% open) over the disturbed area were after Platts et al. (1983).

Additional microhabitat conditions at spawning locations were measured using a 20-m thalweg transect similar to Reiser and Wesche (1977). Information on water depth, channel elevations, gradients and associated water velocities were collected using a laser optic level/stadia rod (Model: Laser-Plane 300) and a Swoffer® flow meter. Elevations and water depth were taken every meter with the spawning area located near the midpoint of the transect. Water column velocities were taken every 0.3 m (0.6-m depth) over the disturbed area and at random locations along the thalweg transect.

Stream discharge was measured weekly at several sites on the main channel (0.0 km, 1.3 km, 3.3 km, 4.8 km and 7.5 km) and for the outlet channel of Gold Creek Pond (0.7 km) using the Swoffer® flow meter. Velocity readings were taken every 0.3 m through the water column depth. Discharge rates were determined by referencing habitat widths, depths, and areas at these sites

The influence of droughts on dewatering periods was evaluated by comparing seasonal variations in rainfall, stream discharge, and baseflow and by determining rainfall–runoff relationships. The units (cm d^{-1}) used in the analysis of rainfall stream discharge and baseflows rates were calculated by the rates being normalized to the appropriate area of the catchment and expressing the values as centimeters per unit time (Dunn and Leopold 1978). The rainfall–runoff relationships were assessed using both flow records measured at 1.3 km and precipitation records (1960 to 1994) from the Stampede Pass Weather Station.

A major assumption of the seasonal hydrological analysis is that baseflow for the Gold Creek catchment is represented by discharge of the Gold Creek Pond. Baseflow is defined as the flow rate that sustains surface streamflows during rainless periods (Dunn and Leopold 1978). Baseflows commonly include groundwaters moving at low velocities through long flow paths before recharging surface waters. Baseflow discharge rates and temperatures tend to be stable over long periods when storage volumes and flow paths of groundwater systems are large. Our observations indicate a majority of the baseflows comes from constant flows of groundwater upwellings and seepage in Gold Creek Pond. The lack of contributions by runoff throughout the catchment (channel reaches and pond) during rainless periods, and lag periods between rainfall and the surface flow responses, can be attributed to high water demand by plants, losses due to evapotranspiration, and water infiltration into soils (Sidle et al. 1985).

Thermographs were used to collect continuous water temperatures in Gold Creek during 1993 (Ryan Inc. chart-type) and 1994 (Onset Inc. digital). Thermographs were placed in the pond outlet at a log weir 70 m downstream from the pond, and at 7.3 km immediately upstream from the confluence of Silver Creek. Thermograph recordings were supplemented with field thermometer measurements throughout Gold Creek.

RESULTS

Habitat Characteristics

Habitats preferred by adult bull trout in Gold Creek during the 1993 and 1994 migration and spawning periods (July through October) were in riffles and pools in the main channels of reaches 1 (0–0.7 km), 4, and 5 (3.3–7.5 km) (Figure 1). Riffle, pool, and glide habitat areas of main channels were 8 to 14 times greater than the those of side channels (Table 1). Reach 5 showed a larger total habitat

Table 1. Preferred reach and habitat characteristics of bull trout for main channels and side channels in Gold Creek, Washington.

Reach	Habitats	n	Area (m^2)	Total Length (m)	Average Length (m)	Average Width (m)	Max. Depth (m)	Sand (m^2)	Gravel (m^2)	Cobbles (m^2)	Boulders (m^2)	LWD 100 m^{-1}
Main channel reaches												
1 (0–0.7 km)	Pool	11	1,935	277	25.2	6.6	1.12	484	1,,258	194	0	4.0
	Riffle	11	2,117	273	24.8	8.1	0.35	318	1,228	572	0	0.0
	Glide	8	3,506	302	37.7	9.6	0.59	386	3,120	0	0	2.3
4 (3.3-4.8 km)	Pool	20	1,498	373	18.6	3.5	0.83	105	839	554	0	4.6
	Riffle	22	1,571	561	25.5	3.1	0.25	0	628	943	0	0.2
	Glide	8	737	191	23.9	3.9	0.44	0	332	405	0	0.5
5 (4.8–7.5 km)	Pool	28	2,250	400	14.3	5.0	1.02	0	1,035	923	270	1.8
	Riffle	38	19,810	2,375	62.5	7.5	0.47	0	5,745	10,697	3,368	1.0
	Glide	14	3,691	435	31.1	7.9	0.55	332	1,661	1,366	332	0.9
Side channel reaches												
1 (0–0.7 km)	Pool	2	178	36	17.8	5.0	0.99	0	142	36	0	0.0
	Riffle	2	320	52	25.9	8.2	0.20	13	288	32	0	0.0
	Glide	1	29	6	6.4	4.6	0.15	0	26	3	0	0.0
4 (3.3-4.8 km)	Pool	1	97	35	35.4	2.7	0.91	29	14	54	0	0.0
	Riffle	3	233	125	41.7	1.4	0.18	0	105	128	0	0.0
	Glide	2	144	47	23.6	3.0	0.24	0	75	69	0	2.1
5 (4.8–7.5 km)	Pool	7	335	81	11.5	4.2	0.92	107	87	80	60	11.1
	Riffle	14	2,290	791	56.5	2.7	0.32	6	298	1,168	687	1.0
	Glide	1	176	32	32.0	5.5	0.94	0	141	35	0	9.4

area in the main channel (25,751 m^2) than reaches 1 and 4 (7,558 and 3,806 m^2, respectively.). The riffle area (19,810 m^2) in reach 5 comprised 53% of the total habitat area.

Greater habitat roughness or fish cover was evident in habitats containing larger-sized substrates (cobbles 65–254 mm; boulders >254 mm) and LWD (Table 1). Cobble deposits were most dominant in reach 5 within riffles (10,697 m^2) and glides (1,366 m^2) of main channels and riffles (1,168 m^2) of side channels. Reach 5 also contained major areas of boulders in riffle habitats of main and side channels (3,368 m^2 and 687 m^2, respectively). Potential fish cover provided by LWD was most apparent in side channels of reach 5 where glide and pool habitats contained 9.4 and 11.1 LWD pieces 100 m^{-1}, respectively. Moderate LWD densities were observed in pool habitats within main channels of reaches 1 and 4 (4.0 and 4.6 LWD pieces 100 m^{-1}, respectively).

The major of accumulations of gravel-sized substrates (2–65 mm) suitable for spawning were in riffles within main channels of reach 5 (5,745 m^2) and glides of reach 1 (3,120 m^2) (Table 1). Reach 1 also showed the most prevalent deposits of sand-sized substrates (<2 mm) in main channels. The pools, riffles, and glides were dominated by sand areas of 484 m^2, 318 m^2 and 386 m^2, respectively. Sand deposits of reach 1 were associated with a low mean channel gradient of 0.7%. Smaller areas of sand deposits in main channels of reach 4 (105 m^2 in pools) and reach 5 (332 m^2 in glides), and side channels of reaches 4 and 5, were consistent with the threefold higher channel gradients (2.4 and 2.5%, respectively).

Bull Trout Spawning Activity

Migrations of bull trout spawning populations in Gold Creek during summer and fall 1993 and 1994 were interrupted when the main channel became dry and impassable. The impassable channel, which included all of reach 2 (0.7 to 1.3 km, Figure 1), resulted from rainfall periods. Areas of dewatering showed some expansion and contraction upstream from 1.3 km during low discharge–rainfall periods. Channel dewatering periods, 12 weeks in 1993 and two 4-week periods in 1994, occurred after the bull trout began migrating into Gold Creek from Keechelus Lake in early summer. The impassable channel, which prevented upstream and downstream fish movements, effectively isolated portions of the bull trout and other fish populations. These fragmented populations enabled weekly snorkel estimates to be made of the relative fish abundance above and below the dewatered reach.

August to November 1993.—For August to November 1993, weekly snorkel surveys indicated that the total bull trout spawning population approached 24 fish. Seventeen fish became isolated above reach 2 when the reach dewatered on August 12. Reach 2 remained impassable to fish from August 12 to November 8. The spawning period for the fish isolated upstream was from September 4 to 16 when temperatures ranged from 9° to 11°C. Of the total 11 redds and 6 test digs observed during 1993 in Gold Creek, 88% of the spawning activity (9 redds and 6 test digs) was between 6.2 and 7.5 km of the main channel (Table 2). For reaches 1, 4, and 5, the major locations of redds and test digs were 53% in riffles, 24% in pools and glides of main channels, and 19% in side channels.

Redd and test dig sites within riffle, pool and glide habitats showed similar mean redd areas (1.6–2.4 m^2), pebble sizes (34.3–40.8 mm), water velocities (0.18–0.25 m sec^{-1}), and depth of cover (0.4–0.9 m) (Table 2). The mean sizes of pebbles indicated that gravels were the dominant substrate (86–97%) in all redds and test digs. Tailout depths (0.08–0.19 m), channel gradient (0.9–2.4%), distance to cover (5.8–18.0 m), and canopy distance (53–98% open) were more variable.

During the August 12 to November 8 dewatering of the channel, seven fish remained downstream. Two of these fish commonly resided in the pond outlet (Figure 1). These fish migrated into the pond during the day to take advantage of thermal refugia supplied by upwelling groundwater at depths greater than 4 m. The other five fish resided in reach 1 (0–0.7 km) and exhibited minimal spawning activity (2 redds) between September 20 and 23.

June to November 1994.—Snorkel surveys were initiated in June 1994 to document possible early arrival times of bull trout in Gold Creek. The snorkel observations indicated several phases of upstream migration and spawning. The first four fish in Gold Creek were located in reach 5 (4.8–7.5 km) on July 13 (Figure 2). Between July 21 and September 9, weekly surveys showed six to eight fish within this upstream reach. These fish became isolated when reach 2 dewatered on July 21. From June 27 to September 14, no fish were observed within reach 2. Fish were first observed downstream of 0.7 km on September 1 with two fish being in reach 1 and four fish in the pond outlet.

On September 14, a peakflow event caused by a rain storm (Figure 3) briefly opened the channel and permitted fish migration. During September 14 and 15, a total of 29 fish were distributed throughout the Gold Creek channel (reaches 1-5). Thirteen fish were counted between reach 1, three fish in the pond outlet, two fish in reach 2 and 3, eight fish in reach 4, and three fish in reach 5. Fish movements during the peakflow event (<1 d duration) indicated migration rates ranged from 2 to 4 km day^{-1}.

After September 15, the channel dewatered again and a majority of the fish were isolated upstream (Figure 2). By September 21–22, 24 fish were isolated upstream with 3 fish being in reach 4 and 21 fish in reach 5. At this time, four fish remained downstream within reach 1 and one fish in the pond outlet.

During 1994, a total of 18 redds and test digs were observed. For reaches 1, 4, and 5, the relative distribution of redds and test digs was 38% in riffles, 31% in pools and glides of main channels, and 24% in side channels. The first upstream spawning activity was observed within reach 4 (3.3–4.8 km) between September 3 and 8 when water temperatures ranged from 9° to 11°C (Figure 4). However, most of the spawning activity (13 redds and 1 test dig) during 1994 was in reach 5 immediately after fish recruitment (September 14 and 15) and during the last 2 weeks of September. During this period, one test dig was observed in reach 4. Downstream spawning activity in reach 1 (1 redd) and within the Gold Creek Pond (2 redds) occurred between October 12 and 21. This late spawning period coincided with decreasing temperatures of the pond and stream waters (Figure 4).

After the spawning period, the number of fish that were within reach 5 decreased from 16 on September 28 and 29 to 6 fish on October 19. Downstream fish movements during this time interval were evident because fish numbers increased from 6 to 15 within reach 4. On October 19, an intense rainfall increased streamflows and opened the entire Gold Creek channel to fish movements.

Bull Trout Mortality

During 1993, eight dead fish and the remains of seven carcasses indicated a mortality of about 63% relative to a population of 24 fish. All the mortalities occurred upstream from reach 2 after spawning. The mortality was attributed to stranding during dewatering and fluctuating water levels near 1.3 km and within the downstream portions of reach 3. The high mortality reflected fish stress and vulnerability during long periods of pre- and post-spawning entrapment, minimal habitat cover, and loss of thermal refugia. Circumstantial evidence also indicated possible fish losses due to predation and poaching.

During the 1994 spawning period, 7 dead fish relative to a total population of about 29 fish pointed to a mortality approaching 24%. Stranding of fish due to channel dewatering during September 21–22 km resulted in two dead

Table 2. Physical characteristics of bull trout redd and test dig sites within riffle, glide and pool habitats during 1993, Gold Creek, Washington.

Habitat	Redds	Channel wetted width (m)	Bankfull width (m)	Redd length (m)[a]	Redd width (m)[b]	Redd area (m^3)	Pebble count (mm)[c]	Tailout depth (m)[d]	Water velocity (m/sec)	Channel gradient (%)[e]	Dist. to cover (m)[f]	Cover depth (m)[g]	Canopy density (% open)[h]
Riffle	Mean	6.6	12.5	2.12	0.87	1.96	34.3	0.10	0.18	2.38	5.8	0.4	53
	SD	5.1	5.9	0.71	0.19	1.05	18.8	0.04	0.11	1.19	7.2	0.2	21
	n	9	9	8	8	8	8	8	9	8	9	9	9
Glide	Mean	7.1	21.2	2.17	1.07	2.40	40.8	0.08	0.25	0.90	18.0	0.4	86
	SD	2.6	5.0	0.55	0.27	1.06	18.7	0.03	0.17	0.34	11.2	0.1	9
	n	4	4	3	3	3	3	4	4	4	4	4	4
Pool	Mean	6.4	18.1	2.27	0.69	1.56	38.1	0.19	0.23	2.14	8.6	0.9	98
	SD	2.0	4.2	0.39	0.03	0.22	17.6	0.10	0.21	1.30	5.7	0.3	3
	n	4	4	3	3	3	3	4	4	4	4	4	4

[a] Redd length is the maximum length of disturbed area (pit and tailspill).

[b] Redd width is the average width of the disturbed area (pit and tailspill).

[c] Pebble count from distribution of 0-200mm size class randomly selected from pit and tailspill (Wolman 1954).

[d] Tailout depth is the minimum depth associated with the disturbed areas tailspill.

[e] Channel gradient is the measured slope of the water elevations 10 m above and below the disturbed area.

[f] Distance to cover is depths greater than 0.2 m with turbulence and or an area capable of shielding the fish from visual contact.

[g] Depth of cover is the maximum depth associated with Distance to cover.

[h] Canopy density was measured with a Spherical Densiometer directly over disturbed area (0 = complete canopy cover,100 = no cover).

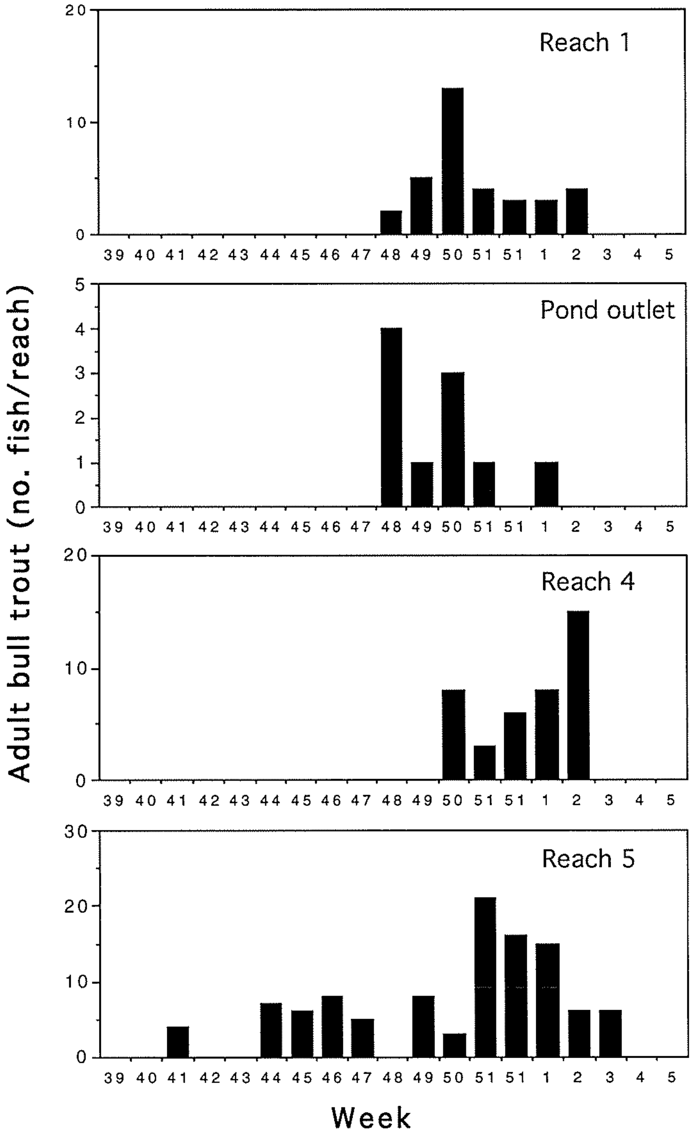

Figure 2. Distribution of adult bull trout within reaches 1, 4 and 5 and the pond outlet during the 1994 bull trout migration and spawning periods in Gold Creek, Washington.

fish in reach 3 and three fish in reach 5. Two additional mortalities were observed within reach 5 on 19 October.

Fish Species Coexisting with Bull Trout

Comparisons were made of the mean relative numbers of bull trout (>30 cm), cutthroat trout (>13 cm), brook trout (>13 cm), whitefish, and kokanee present within different reaches of Gold Creek before and after the September 14–15 peakflow and channel opening in 1994 (Table 3). The before mean values are for weekly observations between August 4 and September 14, 1994, and the after values are for weekly observations between September 16 and October 19, 1994. Weekly snorkel counts showed bull trout, cutthroat trout, brook trout, and whitefish coexisted in reach 1 and in the pond outlet prior to the September 14 peak flow event. The mean numbers of bull trout, cutthroat, brook trout, and whitefish in reach 1 were 1, 8, 5, 26 fish, respectively, and in the pond outlet 1, 1, 5, 25 fish, respectively. No kokanee were present in these waters before September 14.

After September 14, the mean numbers of cutthroat, brook trout, and whitefish decreased while bull trout and kokanee increased (Table 3). The mean numbers of bull trout and kokanee in reach 1 were 5 and 568 fish, respectively, and in the outlet, mean numbers were 1 and 442 fish, respectively.

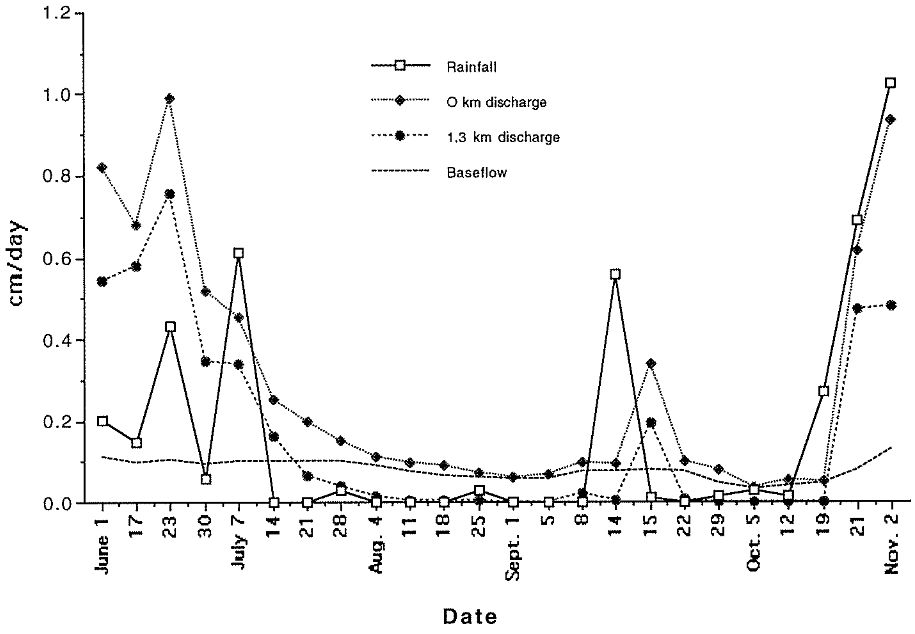

Figure 3. Comparisons of seasonal variations in rainfall, stream discharge, and baseflow (cm d^{-1}) during the 1994 bull trout migration and spawning periods in Gold Creek, Washington.

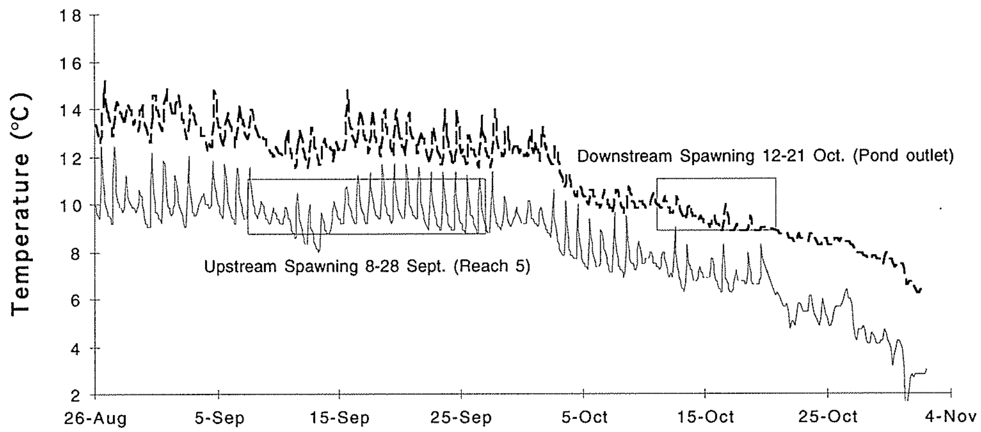

Figure 4. Bull trout spawning periods and water temperatures within reach 5 (September 8 to 28, 1994) and the pond outlet (October 12 and 21, 1994), Gold Creek, Washington.

Although both bull trout and cutthroat coexisted in the upstream reaches, no brook trout, whitefish, and kokanee were observed during the bull trout migration and spawning periods (Table 3). The highest mean densities of cutthroat trout (28 fish) occurred prior to September 14 within reach 5. After September 14, the mean number of cutthroat declined to 11 fish while bull trout densities increased from 7 to 11 fish in reach 5 and from 0 to 9 fish within reach 4.

Day and night snorkeling observations were also made to assess the occurrence of smaller-sized (e.g., juveniles) bull trout (5–30 cm), cutthroat (5–13 cm), and brook trout (5–30 cm) during the bull trout migration and spawning periods. For reach 1, the most diverse fish assemblages occurred during the night with the mean relative numbers of cutthroat and bull trout being 35 and 3 fish 100 m^{-1}, respectively, versus 4 and 0 fish 100 m^{-1}, respectively, during the day. The nocturnal occurrence of potential predators was indicated by the presence of larger bull trout and brook trout (4 fish 100 m^{-1}, respectively) and eelpout (10 fish 100 m^{-1}).

Table 3. Mean relative number of bull trout (>30 cm), cutthroat trout (>13 cm), brook trout (>13 cm), whitefish, and kokanee within different reaches of Gold Creek before and after the September 14–15 peakflow event and channel opening. The before mean values are for weekly observations between August 4 and September 14, 1994, and the after values for weekly observations between September 16 and October 19, 1994. The reaches include 0–0.7 km; the pond outlet; 3.3 and 4.8 km; and 4.8 and 7.5.

Reach	Before/after Sept. 14 peakflow	Weekly observations (n)	Bull trout	Cutthroat trout	Brook trout	Mountain whitefish	Kokanee salmon
1 (0–0.7 km)	Before	6	1 ± 2	8 ± 5	5 ± 3	26 ± 45	0
	After	5	5 ± 4	1 ± 1	1 ± 1	10 ± 22	568 ± 362
Pond outlet	Before	6	1 ± 2	5 ± 6	1 ± 1	25 ± 11	0
	After	5	1 ± 1	0	0	16 ± 34	442 ± 389
4 (3.3 to 4.8 km)	Before	6	0	1 ± 2	0	0	0
	After	6	9 ± 4	7 ± 2	0	0	0
5 (4.8 to 7.5 km)	Before	5	7 ± 1	28 ± 10	0	0	0
	After	6	11 ± 7	11 ± 10	0	0	0

Similar patterns of abundance for small-sized cutthroat and bull trout were observed in the pond outlet during the night (31 fish and 5 fish 100 m^{-1}, respectively) and day (3 fish and 0 fish 100 m^{-1}, respectively). Brook trout did not occur naturally but eelpout were present (18 fish 100 m^{-1}). Few cutthroat and bull trout were observed upstream in reaches 4 and 5 (<1.0 fish 100 m^{-1}, respectively) during night and day. No brook trout and eelpout were observed in the upstream reaches.

Drought and Discharge Controls on Fish Movement

Comparisons of seasonal variations in rainfall, stream discharge, and baseflow facilitate an evaluation of the influence of droughts on dewatering periods. A major consideration is the observation that discharge from the pond represents the watershed's baseflow (see Methods). This observation is substantiated by several data sets. First, the capacity of baseflows to sustain downstream surface flows during rainless periods is evident in pond outlet discharge rates being high (68–95%) relative to flows downstream (0 km) during the 1994 dewatering periods. Second, the pond discharges are relatively constant during both August to November 1993 (0.08 ± 0.02 cm d^{-1}, n = 14) and June to November 1994 (0.08 ± 0.03 cm d^{-1}, n = 25) (Figure 5). Third, the relatively constant and cool temperatures of the pond's upwelling (7.2 ± 0.3°C, n = 13) and discharge waters (11.4 ± 1.6°C, n = 16) point to groundwater sources of water rather than surface runoff.

Changes in rainfall, stream discharge, and baseflow (cm d^{-1}) for the Gold Creek watershed are compared for June through November 1994 (Figure 3). On July 21, the the streamflow at 1.3 km (0.06 cm d^{-1}) at the head of the dewatered reach (reach 2) became less than the baseflow (0.10 cm d^{-1}). Streamflow rates at 1.3 km remained less than baseflow for both the subsequent dewatering periods, 21 July to September 14 and September 15 to October 19, 1994.

For the two dewatering periods, the average streamflow at 1.3 km was 0.01 ± 0.02 cm d^{-1} (n = 13) or 14% of the baseflow (0.07 ± 0.02 cm d^{-1}, n = 14). This average streamflow excludes the peak flow event of 0.19 cm d^{-1} on 15 September 1994, which was initiated by high rainfall (0.56 cm d^{-1}). After the peak flow response, the channel became dewatered by 16 September. Surface flows did not resume until the next high rainfall (0.27 cm d^{-1}) on October 19. High rainfalls after this date sustained surface flows in stream channels during the late autumn and allowed fish to migrate downstream to the lake.

The average rainfall of 0.01 ± 0.01 cm d^{-1} (n = 15) during the two dewatering periods represents daily precipitation levels that were less than the mean baseflow (0.07 ± 0.02 cm d^{-1}, n = 14). A regression analysis of the relationsh between daily rainfall (cm d^{-1}) for the watershed and discharge (cm d^{-1}) at the 1.3-km channel site for June through November 1994 shows a direct relationship:

$$y = 0.10 + 0.55X,\ R^2 = 0.42,\ n = 25$$

The intercept of this equation indicates dewatering of the channel occurs at streamflows less than 0.10 cm·d^{-1} when

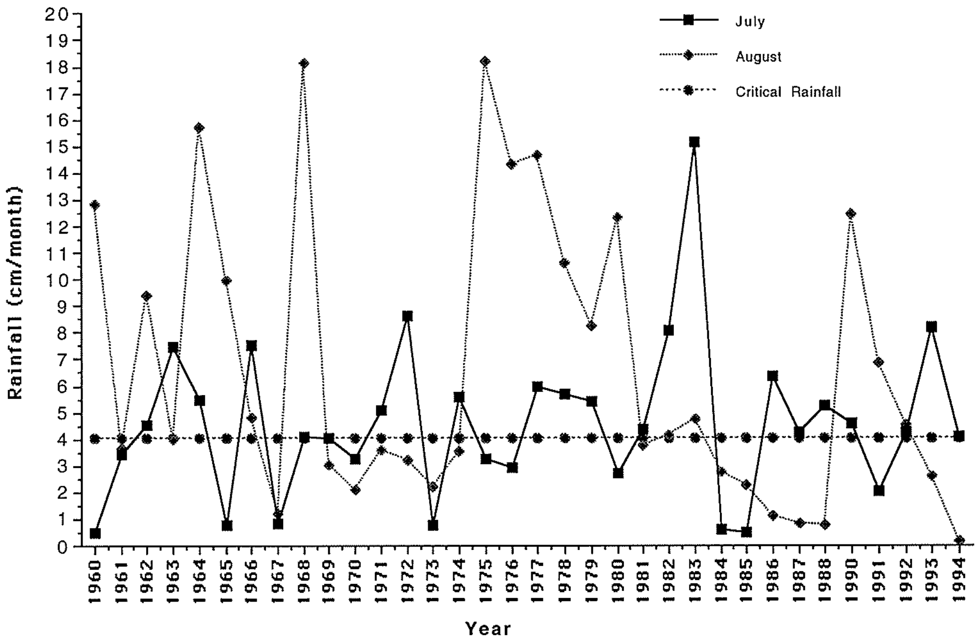

Figure 5. Comparison of monthly precipitation records (1960–1994) for July and August (Stampede Pass Weather Station, Washington) to a critical rainfall rate (<4 cm month^{-1}) that could cause the dewatering of Gold Creek.

rainfall lacks the capacity to recharge surface flows. During such periods, both rainfall and surface discharge rates are lower than baseflow (Figure 3).

A regression analysis of the monthly rainfall–runoff relation indicates that low monthly streamflows are also directly related to declining rainfall levels ($R^2 = 0.58$). The regression for 7 months (June to October 1994 and August and September 1993) indicates dewatering occurs when rainfall is less than 4 cm month^{-1}.

A comparison of a rainfall level of 4 cm month^{-1} to monthly precipitation records (1960 and 1994) indicates the historical frequency of occurrence of when rainfall is less than 4 cm month^{-1}. The records indicate monthly rainfalls below 4 cm month^{-1} were more frequent during July and August (35% and 50%, respectively) than September and October (18% and 6%, respectively) (Figure 5). However, during a 10-year drought (1984–1994), the frequencies increased for the low-flow months (July to October), ranging from 30–70% for the 1984–1994 interval. Higher frequencies of 40% for October indicate longer dewatering periods and potential stresses on fish.

DISCUSSION

The isolation of the adult bull trout population and mortality of spawners in Gold Creek occurred during both summer and fall 1993 and 1994 when main channels became dry and impassable. Dewatering in reach 2 effectively fragmented the bull trout population and imposed spatial constraints on the distribution other fish (brook trout, cutthrout, kokanee). We conclude that hydrological factors, specifically channel dewatering, were the major factors controlling adult bull trout distribution and survival.

Our findings for Gold Creek indicate that bull trout spawning mortalities increased when spawning periods coincided with long periods of drought and dewatering of channels. Field observations in Gold Creek indicate that the fish may experience from 20% to 30% mortality during 1 month of channel dewatering and 60–70% during 2 months of dewatering. These mortality rates are comparable to those observed for other bull trout populations: For example, spawning mortalities of 30–40% in tributaries of the Flathead River (Fraley 1985), total annual mortalities of 47–82% in the Pend Oreille drainage (Pratt 1992), and annual harvests of about 40% in Flathead Lake (Hanzel 1985).

We hypothesize that high mortalities of spawning bull trout could have occurred during historical drought and channel dewatering periods. When successive years of droughts and channel dewatering coincided with spawning periods in Gold Creek and other streams in the Cascade Mountains, high mortalities of spawners possibly reduced the population's survival.

A retrospective view of the yearly survival of bull trout spawning populations during drought-induced dewatering periods can obtained by using variable mortality rates and by considering the fish's unique life-history characteristics. Continuous recruitment of bull trout spawners, which usually begins at age 5 when the fish become sexually mature, can produce mixed-age spawning populations of about 5 to 12 years in streams on the east side of the Cascade Mountains (Brown 1992). These fish are capable of spawning several times throughout different years but not in successive years (Bjornn 1991). We suggest that these spawning patterns evolved to increase the survival of fish in natal streams that experience extreme environmental conditions (e.g., droughts and peak flow events).

Our retrospective analysis applies a mixed-aged survival index to assess the potential survival of the bull trout spawning population. The major assumptions of the analysis include the following: (a) the total population of all ages of spawners present at the beginning of any year represents spawner recruits of mixed ages, (b) adult fish can survive several years of "natural" mortality, and (c) the fish spawn several times during their life span.

The mixed-aged survival index (S_m) is modified from Ricker (1958) and predicts the total number of recruits present in the spawning population at the beginning of the year. S_m is calculated by summing the geometric series

$$S_m = a_1/i_1 + s_2a_1/i_1 + s_3s_2a_1/i_1 + s_4s_3s_2a_1/i_1 \qquad (1)$$

where i = instantaneous rate of mortality of spawners,

a = annual rate of mortality, and

s = the annual survival rate.

The geometric series for this simulation includes four recruitment years: a_1/i_1 = the number of surviving recruits of a first year, s_2a_1/i_1 = survivors in the second year, $s_3s_2a_1/i_1$ = survivors in the third year, and $s_4s_3s_2a_1/i_1$ = survivors in the fourth year.

The predicted S_m values are calculated for varying rates of mortality (i and a) and annual survival (s). The instantaneous rate of mortality (i) is based on the observed spawner mortalities in Gold Creek during critical months of drought and channel dewatering. The critical months are identified as rainfall rates less than 4.0 cm month^{-1}. Instantaneous mortality rates are assumed to be 0.20 during non-critical months, 0.30 for 1 month of dewatering, and 0.70 for 2 successive months of dewatering. The assumed instantaneous rates are then assigned to June, July, and September of each year according to the frequency of occurrence of critical drought–dewatering months during a 30-year rainfall record (1960–1994, Figure 5). The corresponding annual mortality (a) and survival rates (s) are from Ricker (1958).

The S_m values for bull trout spawning populations in the Gold Creek catchment (1964 and 1994, Figure 6) indicate lower survival of fish following 2 months of dewatering. However, the lowest survivals of 1.3 to 1.6 for the

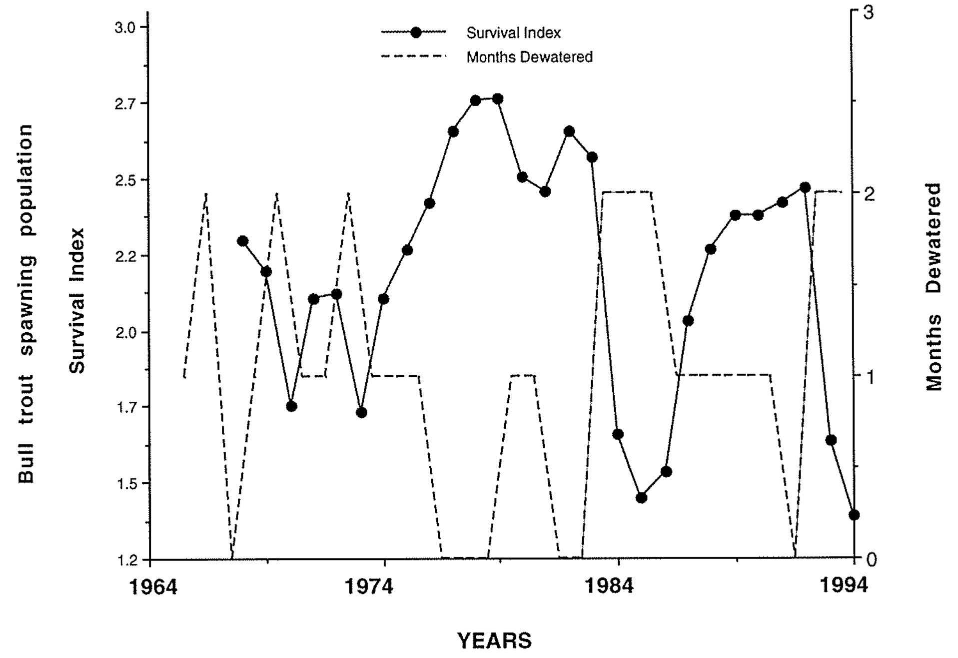

Figure 6. Survival values (S_m) for bull trout spawning populations in the Gold Creek catchment (1964 and 1994). S_m represents a mixed-aged survival index modified from Ricker (1958) to predict the total number of recruits present in the spawning population at the beginning of any year.

years 1984 to 1986 and 1993 to1994 correspond with 2–3 consecutive years having long dewatering periods. Consecutive years of 2 months of dewatering, when instantaneous mortalities of spawners approached 70% per month, suggest cumulative impacts on long-term survival. Conversely, the S_m shows survival increased (1.9–2.4) during 5 continuous years (1987–1992) having 1 month of dewatering per year (30% mortality per month). The highest S_m values (2.6–2.7) occurred after 3 consecutive years (1977–1979) when no dewatering occurred (20% mortality per month).

We suggest that the potential for adult bull trout of mixed-age spawning populations to spawn during different years depends on fish surviving several years of natural mortality. Accordingly, S_m for the total number of recruits present in the spawning population at the beginning of the year increases when recruits of mixed ages experience high survival rates during one to several previous spawning years. Conversely, when consecutive years of survival are low for mixed ages, additional sources of mortality and longer periods of dewatering could be devastating. For example, severe losses could occur because of poaching, which has the potential to increase with the duration of channel dewatering and fish exposure in streams.

CONCLUSION

This study shows that frequent isolation of spawning bull trout populations in habitats of small mountain streams can significantly decrease fish survival. Lower survival may be especially evident in streams like Gold Creek where fish must spawn in shallow riffle and pool habitats that provide poor cover. These habitats are highly sensitive to frequent alterations caused by hydrological, erosional, and depositional processes, and related anthropogenic modifications. Such local-scale habitat and reach conditions, when altered by the combined forces of human actions and natural disturbances (e.g., droughts and floods), undoubtedly lead to marginal environments and longer periods of stress that, in turn, depress fish populations.

Duration of channel dewatering may be longer in small streams because of climatic and geomorphic interactions and impacts of human modifications. While the duration of channel dewatering increases during years of below-normal precipitation, dewatering during droughts may be prolonged even further. For example, dewatering periods in Gold Creek may be longer than "normal" because of the placement of the pond in the valley floodplain. This artificial pond was created by the excavation of a gravel pit within low-gradient floodplains adjacent (150 m) to reach 2. During droughts, the pond may cause flow patterns of subsurface waters to downwell into the groundwaters and flow into the pond for longer time periods. Such altered flow patterns could cause potential delays in the capacity of rainfall to recharge surface waters in channels.

In larger river systems, bull trout populations may have greater opportunities for survival because of increased habitat diversity and connectivity, and water availability. For example, a study of adult bull trout migration in the Blackfoot River of Montana indicates that bull trout frequently use pool habitats of channels that are highly connected to other portions of the river basin (Swanberg 1996). This study demonstrated bull trout migration distances within the Blackfoot River averaging 63 ± 21 km, greater migration distances by spawning fish than nonspawning fish, migration rates ranging from 1.9 to 11.8 km d^{-1}, lower daily migration rates for spawning than nonspawning fish, and increases in daily migration rates at higher temperatures and within downstream reaches.

The geographic scales and habitat separation distances required by bull trout in the Blackfoot River not only points to the importance of the life-history requirements of spawning populations but to the potential exchange of genetic materials between populations across riverine landscapes. The diversity of bull trout phenotypically is apparent in age and size at maturity, ≠±=spawning timing, fecundity, and egg size, among many heritable traits (Bjornn 1991). Such population attributes were undoubtedly lost by bull trout of the Gold Creek–Keechelus Lake catchment when the construction of a dam in 1911 effectively isolated the fish from the Yakima River and large networks of adjoining tributary rivers.

The spawning characteristics of bull trout suggest that different populations could vary in their susceptibility to anthropogenic modifications. At the local scale, the spawning or breeding populations appear to be the primary demographic and genetic units that operate in variable environments on relatively short evolutionary scales. The potential for partial isolation of local breeding populations allows the evolution of adaptations to local environmental conditions (Allendorf 1983). Disruption of the evolutionary responses of fish populations at local scales by anthropogenic actions could alter the diversity of life-history patterns that tend to develop and be expressed under different natural conditions (e.g., hydrologic, climatic, habitat, and physiographic). Similarly, anthropogenic modifications could also alter how populations are structured at regional geographic scales.

Findings of the National Research Council (1995) suggest that the potential exchange of genetic material between salmonid populations at regional geographic scales could play an important role in the differences in vulnerabilities of fish stocks to anthropogenic modifications. A geographic population network, or metapopulation, could connect local breeding populations and therefore the diversity of life-history patterns needed to sustain fish productivity at both the local and regional geographic scales (Hanski and Gilpin 1991, Riddell 1993). The metapopulation concept suggests that the infrequent exchange of individuals (e.g., straying of spawning fish) ensures that all the alleles within the metapopulation are available to each local population (Allendorf 1983). Such a hierarchy of levels of genetic diversity could provide a basis for maintaining diversity in gene pools and population structure on evolutionary time scales longer than several fish generations (Riddell 1993).

Anthropogenic disruption of bull trout populations at the geographic scale could cause a loss in the balance between local adaptation and the evolutionary opportunities that result from the exchange of genetic information. Potential fish responses include altered and possibly reduced geographical distributions in terms of discrete spawning populations adapted to the environmental conditions. Such changes could cause a reduction in the diversity of bull trout spawning populations needed to sustain fish productivity at both the local and regional geographic scales.

Future research on bull trout should focus on the conservation of genetic diversity and organization of fish populations (local and metapopulation) at different geographical scales. Considerable attention should be given to defining (1) relationships between life-history patterns and the dynamics of metapopulations and (2) the genetic and evolutionary risks of management practices and uses of natural resources. A better understanding is also needed of the variability of fluvial ecosystems and their spatial and temporal scales. Such perspectives are especially important to ecosystem managers who desire to restore and sustain bull trout populations, habitats, and the connectivity of riverine systems (Wissmar, in press; Wissmar and Beschta in press).

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