A Review of the Effects of Flow on Brown Trout

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Spawning requirements

For spawning of brown trout *Salmo trutta* in New Zealand, the mean water velocity was 39.4 cm/sec (range, 15-75 cm/s (Shirvell and Dungey 1983). For anadromous brown trout in Lithuania, females created redds in velocities of 40-70 cm/s at depths of 25 to 40 cm (Nika et al. 2011). Brown trout spawned in flows ranging from 21-600 L/sec in Ontario, Canada (Witzel and MacCrimmon 1983). In the UK, redds of brown trout, rainbow trout *Oncorhynchus mykiss*, and Atlantic salmon *Salmo salar* were found in velocities greater than 15-20 cm/sec (Crisp and Carling 1989); maximum velocities varied with the size of the female, ranging from about 30 cm/sec for 20 cm long fish to about 100 cm/sec for fish ≥ 60 cm. In Douglas Creek, Wyoming, 20-40 cm brown trout selected water depths of 12-18 cm with velocities of 24-37 cm/sec for their redds (Grost et al. 1990).

Effects on eggs and redds

Eggs of brown trout, like other salmonids, are laid in gravel redds. The eggs are deposited as the female flexes her body, covering the eggs with gravel, creating a depression in the streambed with a tail-spill mound at the downstream end of the depression (Grost et al.1991). The eggs have been found at depths between 0 and 25 cm deep (typically 9-12 cm) in the gravel (Ottaway et al. 1981; Grost et al. 1991). Egg deposition depth is partially dependent upon female size, i.e., larger brown trout may bury their eggs deeper (20-30 cm; Hobbs 1948; Stuart 1953). Rocks > 50 mm were used as centrums for redd location and particles < 6.3 mm in diameter were typically cleaned away from the redd (Grost et al. 1991). Redds are not cleaned to a specific standard, so particle composition is related to the surrounding stream substrate (Grost et al. 1991). For brown trout redds in Ontario, Canada (Witzel and MacCrimmon 1983), mean water depth was 25.5 cm, mean stream velocities were 46.7 cm/sec, and the geometric mean sediment size in the redd was 6.9 mm. In New Zealand, spawning brown trout preferred a mean depth of 31.7 cm and a mean substrate size of 14 mm (Shirvell and Dungey 1983). Average brown trout redd length was 147 mm in Douglas Creek, Wyoming (Grost et al. 1990). In the UK, fish preferred gravels of 20-30 mm diameter and redds were found at water depths of 4-5 cm to about 52 cm (Crisp and Carling 1989). Groundwater inflow can affect redd site selection; Hansen (1975) observed that female brown trout avoided sites which had undiluted groundwater inflow, but redds were found in either mixed water (surface and groundwater) or surface water infused sites characterized by higher dissolved oxygen concentrations.

Varying periods of dewatering might be expected to very detrimental to incubating eggs, but observations of redds of brown trout eggs (Hobbs 1937; Hardy 1963) as well as other salmonid eggs (Hawke 1978; Reiser and White 1983) have indicated that the eggs are surprisingly resilient and will survive if surrounding sediments maintain at least 4% moisture by weight (Reiser and White 1983).
However, if eggs are frozen, due to exposure during dewatering or to persistently frigid temperatures that freeze redds even in good habitat, survival will likely be less than 1% (Reiser and Wesche 1979). Despite good egg survival, alevins exposed to moist, but dewatered conditions, will quickly die (Reiser and White 1981; Becker et al. 1982).

High flows generally have little effect on redds (Nelson 1986; Jensen and Johnsen 1999). However, one study on Sagehen Creek in California indicated that winter flooding was detrimental to brook trout *Salvelinus fontinalis* (Seegrist and Gard 1972). Attempts to use fluctuating flows to control rainbow trout abundance in the Colorado River increased incubation mortality rates to an estimated 23-49% compared to 5-11% under normal flow fluctuations (Korman et al. 2011); however, there was strong compensation in fry survival.

**Effects on alevins**

Newly hatched brown trout prefer water velocities of ≤ 20 cm/sec (Armstrong et al. 2003; Bardonett and Heland 1994). Jensen and Johnsen (1999) found that highest mortality of brown trout in a Norwegian river occurred when spring floods coincided with the alevin stage; low water temperature at the time of 50% emergence also negatively affected survival (exact temperatures not given, but < 8 C negatively affected Atlantic salmon alevins). A few controlled studies have examined flow effects on brown trout alevins. Ottaway and Clarke (1981) found that displacement of brown trout fry (23 to 25 mm long) in a simulated stream was correlated with surface velocity; the relationship was expressed as $y=64.4X^{0.9}$ in one trial and $y=12.1X^{0.6}$ in another, where $y =$ the percentage of the fry population displaced and $X =$ surface velocity (m/sec); more than half of the population was displaced at velocities exceeding about 0.5 m/sec in 1 m wide channels. Heggenes and Traaen (1988) tested flow effects on brown trout at swim-up, 2, and 8 weeks-old at temperatures of 6-8 C or 12-19 C. Fry withstood higher velocities at the higher temperature. Maximum critical velocities at the lower temperature were around 0.15 m/sec in 20 cm wide experimental channels for swim-up fry and 0.23 m/sec for '2 week' fry; '8 week' fry could not be completely washed out of the channels. In experimental channels, Crisp (1991) observed that brown trout alevins had low downstream dispersal at low water velocities (8.0 cm/s), but dispersal increased with flow; Dispersal was greater at night than by day. Velocities in excess of 25 cm/sec led to increasingly higher displacement rates (Crisp and Hurley 1991a). Daufresne et al. (2005) compared downstream displacement of 0, 3, and 12 day-old alevins at constant (12 cm/sec) and variable velocity (33 cm/sec) and found that displacement occurred earlier at the higher velocity, but both systems had comparable total displacement rates (80%). Displacement may have been affected as much by density as velocity (Crisp 1991; Daufresne et al. 2005). Alevins up to 5-6 days-old were especially sensitive to increased flows. Fluctuating flows led to higher displacement of brown trout alevins than constant flow (Crisp and Hurley 1991b). High fluctuations in flow can lead to stranding, failure of seedling establishment, as well as flushing of fry, invertebrates, and organic matter (Crisp and Hurley 1991b; Poff et al. 1997).

**Effects on juvenile and adult fish**

Wesche et al. (1987) found that the best predictors of brown trout standing stock (kg/ha) were measures of cover, a fishing pressure index, and base flow (mean annual base flow expressed as a
percentage of mean annual daily flow). Brown trout parr were reported in shallow riffle habitat with moderate velocities (20-50 cm/sec), moving to deeper water as they grow (Armstrong et al. 2003; Crisp 1993). Increases in minimum flows have been documented to help brown trout populations. E.g., Wolff et al. (1990) noted that increasing minimum flows in a regulated river from 1 to 5.5 cfs doubled brown trout abundance in one reach and in another reach there was a four- to six-fold increase. The latter reach, downstream of a diversion, had a wetted width that doubled with the increased flow and weighted usable area for adult fish was almost 5 times greater. On the Beaverhead River, Montana, fluctuating flow [decreases of 6.6-18.1 m$^3$/sec (54-74%), followed by or preceded by increases of 6.7 - 14.5 m$^3$/sec (80-369%)] during brown trout spawning in mid to late October, was associated with poor recruitment of yearlings (Nelson 1986). However, the magnitude of the flow during spawning and potentially stranding flows were not correlated with yearling recruitment; Nor was there a correlation between yearling brown trout abundance and flows during incubation and rearing (Nelson 1986). High discharge during egg incubation did not affect year class strength of either brown trout or Atlantic salmon Salmo salar (Jensen and Johnsen 1999); the mortality of ≥ 1-year-old fish was similarly unaffected by high discharge. Adult rainbow and brook trout were generally unaffected by all but the largest floods in a California creek (Seegrist and Gard 1972). Similar lack of flow effects during winter were observed in the Au Sable River of Michigan (Nuhfer et al. 1994). However, Nuhfer et al. (1994) found that brown trout recruitment to age 0 was inversely related to mean daily flow during the spring when fry would initiate feeding for the first time; not surprisingly, multiple high flow events during this period were more likely to impact recruitment. Liebig et al. (1999) found that high hydropeaking flows characterized by 2-fold increases in rapid and glide depths and up to 4-fold increases in riffle depth, as well as 10-fold increases in run velocities, led to significant declines in young-of-year brown trout abundance.

**Indirect effects of flow**

Associated with changes in water flow are other variables that could affect fish abundance, e.g., number and diversity of invertebrates, stream/pool width and depth, water temperature, sediment load, flushing of plant material, and water quality (reviewed by Cushman 1985). Benthic invertebrates, which fish rely on for food, may be negatively affected by flow, especially rapidly fluctuating flow (Fisher and LaVoy 1972; Williams and Winget 1979; Cushman 1985). Fjellheim et al. (1993) noted that a 4-8X increase in flow was associated with reductions in chironomid larval biomass (≤3.8% of biomass at normal flow), as well as caddis larvae (e.g., Apatania and Oxyethira spp.). Moog (1993) observed a 75-95% reduction in invertebrate biomass in the first few kilometers downstream of dams that had fluctuating flows (maximum to minimum flow ratios of 40-60 to 1); even 20-40 km downstream, 40-60% reductions in biomass were noted. However, if flow variations are within natural seasonal variations, invertebrate life history patterns may be unaffected (Liebig et al. 1999).

**Effects of sediment**

Flows can have an effect on fine sediment, the deposition of which generally increases as flows are reduced. Conversely, higher flows flush fine sediments downstream. Brown trout do not clean the
redds after deposition, so sediment accumulation in egg pockets during egg incubation occurs over winter (Hobbs 1948; Stuart 1953; Chapman 1988; Grost et al. 1991). Grost et al. (1991) observed microhabitat differences in fine sediment accumulation within a redd; higher proportions of fines were found in the pocket than in the surrounding redd or streambed. Maret et al. (1993) found an inverse correlation between the percentage of fine sediment and survival of brown trout to fry emergence. Bjorn et al. (1977; summarized in annotated bibliography by Kerr 1995) suggested that when the percentage of fines exceeds 20-30% in spawning riffles, then survival and emergence of salmonid embryos begins to decline. In a meta-analysis of Pacific salmon studies (Jensen et al. 2009), egg-to-fry survival began to drop significantly when the percentage of fines <0.85 mm was >10%; for larger sediment sizes, the percentage was 25-30%. Levasseur et al. (2006) observed sharp reductions in Salmo salar embryo survival if the percentage of silt and very fine sand (<0.125 mm) was >0.2% of the redd gravel. Sediment accumulation can also affect salmonids by filling pools and interstitial habitat where invertebrates can be reduced in number or displaced (Bjornn et al. 1977; Berkman and Rabeni 1987).

Although not always correlated with low dissolved oxygen (Sowden and Power 1985; Fudge et al. 2008), fine sediments can reduce the oxygen available to eggs as well as physically trap alevins in the gravel (Coble 1961; Phillips et al. 1975). Maret et al. (1993) noted that brown trout survival to fry emergence was correlated with intra-gravel dissolved oxygen concentration, with the best survival observed above 70% saturation (8 mg/L). Young et al. (1990) observed that the geometric mean of particle size was a better predictor of survival to emergence of brown trout than the percentage of fines less than a given size. Witzel and MacCrimmon (1983) noted reductions in egg survival (only 0-20%) in homogeneous gravel of 6.2 mm or finer or in heterogeneous gravel with 60% or more of sand, whereas gravel of 9.2 mm or heterogeneous gravel with 20% or less was associated with 60-96% survival. Higher proportions of fine sediment can also reduce invertebrate diversity and abundance (Tebo 1955; Milner et al. 1981; Newcombe and MacDonald 1991; Henley et al. 2000).

**Temperature**

To estimate the effect of flows on emerging brown trout, it is helpful to understand when emergence might occur. If the spawning period is known for a given location, then the hatching date can be estimated based on incubation temperature. The relationship between days required to hatch brown trout eggs and temperature is shown in Figure 1 (data from Gray 1929, Embody 1934, Humpesh 1985). This relationship can be expressed as a power law (Crisp 1981; Humpesh 1985): Days=aT\(^b\), where T is temperature (C) and a and b are constants over a range of 1-15 C; for brown trout from a variety of European populations, the a and b constants averaged 281 (5-95 percentile confidence limit of 268-294) and 0.84 (0.84-0.84), respectively. The number of degree (C)-days needed to hatch brown trout eggs studied by Jungwirth and Winkler (1984) ranged from 478.8 at a constant 2 C incubation temperature to 385.6 °C-days at 16 C; the mean was 430.4 °C-days.
In summary, water flow rates and their variation can have varied and complex effects on aquatic ecosystems. These effects may directly influence the survival and behavior of life stages of fish, invertebrates, plants, and other animals, as well as the physical habitat for these organisms. Indirect effect of flows on organisms, such as water temperature, sedimentation, and water quality also must be considered for flow management to achieve biological objectives. For brown trout, flows and flow variation during emergence of fry are of particular important for survival.

**Literature Cited**


