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EMBRYO SURVIVAL, SUBSTRATE COMPOSITION, AND DISSOLVED OXYGEN IN REDDS OF WILD BROOK TROUT

by

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ABSTRACT

Survival of brook trout (Salvelinus fontinalis) embryos and alevins in redds and factors affecting their survival were studied in two undisturbed headwater streams, supporting natural reproduction of brook trout, on Pennsylvania's Allegheny Plateau. Both study streams supported relatively high numbers of trout but average size of trout was small. Estimated population was 6,067 fish/hectare and 58 kg/hectare in one stream and 4,507 fish/hectare and 60 kg/hectare in the other.

Redds were often located immediately upstream of a small pool or a buried log. Egg pockets were about 5-10 cm below the gravel surface and were sometimes located in a gap between two large stones. Diameter of wild brook trout eggs averaged 4.6 mm. Mean intragravel dissolved oxygen concentration in 36 redds ranged from 3.7 to 10.5 mg/liter but usually exceeded 6 mg/liter. Intragravel and surface water temperatures were similar. Geometric mean particle size of redds ranged from 0.6-mm coarse sand to 14.2-mm gravel with a grand average of 3.3 mm.

Estimates of survival to eyed egg, corrected for decay and loss of dead embryos, ranged from 0 to 100% and averaged 69%. Survival was related directly to mean dissolved oxygen concentration and inversely to substrate particle size. Based on the total number of eyed embryos recovered and the estimated number of eggs deposited in redds, survival to eyed egg was 39%. Emergence success from 10 artificial redds stocked with eyed eggs averaged 34% and ranged from 5 to 92%. Fry began emerging

in February but peak emergence was in March and early April. Emergent fry averaged 22.5 mm long and 0.067 g in weight. In both streams, estimated egg deposition was about 53,000 eggs/hectare and an average of 1,593 young-of-the-year/hectare were present. Thus, survival from egg deposition to fall fingerling was approximately 3%. Survival from egg deposition to emergence was estimated to be 23%. Survival in redds was apparently adequate to sustain these brook trout populations at relatively high densities.

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INTRODUCTION

Historically, brook trout (*Salvelinus fontinalis*) occurred in most Pennsylvania streams, but habitat degradation reduced their distribution (Fowler 1940; Hazzard [no date]). One of the last areas of Pennsylvania where brook trout remain the dominant wild trout and where small stream fisheries for wild brook trout are important is the Allegheny Plateau. This study was conducted on undisturbed headwater streams with good natural reproduction of brook trout, typical of many on the Allegheny Plateau.

The objectives of my study were to:

1. assess the standing stock, age structure, and potential egg deposition of wild brook trout,
2. measure the temperature and dissolved oxygen content of intragravel water and substrate composition of brook trout redds, and
3. estimate the survival of brook trout embryos from egg deposition to eyed stage and to emergence.

Survival of embryos in redds depends on dissolved oxygen and intragravel water velocity sufficient to deliver adequate oxygen and remove waste products (Silver et al. 1963; Shumway et al. 1964). Well oxygenated stream water provides the source for recharge of poorly oxygenated intragravel water (Sheridan 1962). Interchange of stream and intragravel water is controlled by gravel permeability, stream bed depth and irregularity, and curvature of the stream water surface (Vaux 1962, 1968; Cooper 1965).

Field observations of salmon and trout have correlated survival of embryos and alevins with areas of higher dissolved oxygen and intragravel water velocity (Wickett 1954; Coble 1961; Bianchi 1963; Peters 1965; McNeil 1966; Wells and McNeil 1970). Gravels with increased proportions of sand and fines yielded poorer survival of embryos and alevins (Wickett 1958; Bianchi 1963; McNeil and Ahnell 1964; Peters 1965; Bjornn 1969; Hall and Lantz 1969; Rukhlov 1969; Dill and Northcote 1970a, 1970b; Phillips et al. 1975; Hausle and Coble 1976). Sublethal levels of dissolved oxygen delay the rate of development of salmonid embryos resulting in deformed and weak alevins (Alderdice et al. 1958; Silver et al. 1963; Shumway et al. 1964). Low oxygen levels during latter stages of development can cause premature hatching (Alderdice et al. 1958; Garside 1966; Bams 1969).

Brook trout have been observed to spawn in springs and areas of groundwater inflow and may prefer these areas (White 1930; Greeley 1932; Hazzard 1932; Ricker 1932; Brasch 1949; Benson 1953). Temperature differential between stream and intragravel water of redds has indicated that redds were located over or adjacent to upwelling groundwater (White 1930; Benson 1953; Griswold 1967; Hunt personal communication[1]). Groundwater flow and velocity may be more important than substrate in determining the site selected for spawning (Webster 1962, 1975).

Brook trout spawn in sand, fine gravel, and gravel substrate (Greeley 1932; Hazzard 1932; Ricker 1932; Brasch 1949; Benson 1953; McFadden 1961; Webster 1962). Several investigators noted lower survival of brook trout embryos and alevins in sandy redds (Brasch 1949; McFadden

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[1]R. L. Hunt, Group Leader, Wisconsin Department of Natural Resources, Coldwater Research Group, Waupaca, WI.

1961; Webster 1962; Miller 1970). However, except for studies by Hausle and Coble (1976) and Reiser and Wesche (1977), no quantitative evaluations of the particle size composition of natural redds have been made.

Survival of brook trout embryos and alevins in redds is generally considered to be high. Better than 90% survival of wild embryos has been observed in laboratory experiments (Hale 1968; Hale and Hilden 1969; Hokanson et al. 1973; Benoit 1974). Survival under natural conditions has been estimated to be between 29 and 94% when natural redds were excavated (Hazzard 1932; Brasch 1949; McFadden 1961; White 1965; Miller 1970; Hausle and Coble 1976). However, there probably was even more variation as these studies also noted redds with very low or no apparent survival of embryos, especially in sandy substrate. In addition, the numbers of eggs deposited and, except for the study by Hausle and Coble (1976), the disintegration of dead embryos were unknown; therefore, these survival estimates may be biased. Estimates of survival from egg deposition to fall fingerling have ranged from 2 to 16% (Smith 1947; Cooper 1953; McFadden 1961; Shetter 1961; McFadden et al. 1967). Heavy losses were assumed to occur after emergence because it was assumed that survival in redds was high.

Little is known of brook trout emergence success from natural redds. Miller (1970) found a 70-fold difference between the estimated number of eggs deposited and the number of emergent fry observed. As relatively few fry emigrated, mortality before emergence was implicated. Hausle and Coble's (1976) attempts to trap fry as they emerged from redds failed because the traps collected sand, smothering the redds. Brasch (1949) succeeded in trapping five redds in a spring pond and estimated 79% emergence. In a laboratory experiment, Hausle and Coble (1976) found emergence decreased with increasing sand in redds, but emergence was never less than 82%, even in 25% sand.

DESCRIPTION OF AREA

Study areas were chosen on Smays Run and Benner Run, two small, infertile, headwater brook trout streams typical of many on the Allegheny Plateau. The streams were chosen because they:

1. support wild brook trout populations, have natural reproduction, and lack brown trout (*Salmo trutta*),
2. are infertile and weakly buffered,
3. are in state ownership and relatively unspoiled by humans,
4. have background data available on the trout populations,
5. are not stocked or heavily exploited by anglers, and
6. are reasonably accessible and within about one hour's driving distance of my office.

The study streams are located in Centre County, Pennsylvania, at roughly 40° 55' N latitude 78° 1' W longitude in the West Branch Susquehanna River Basin (Fig. 1). They arise about 5 km apart at 610 m elevation and flow west through northern hardwood forests of mixed oaks and scattered conifers. Bank vegetation in open areas consisted of grasses and sedges, but most areas were densely shaded by hemlock (*Tsuga canadensis*), rhododendron (*Rhododendron maximum*), and sometimes by oak (*Quercus* sp.) and tag alder (*Alnus rugosa*). Almost horizontal beds of gray, hard, massive crossbedded conglomerate and sandstone of the Mississippian period with some shales underlie the basin. Ridge tops are capped by sequences of sandstone, conglomerate, shales, and coals of

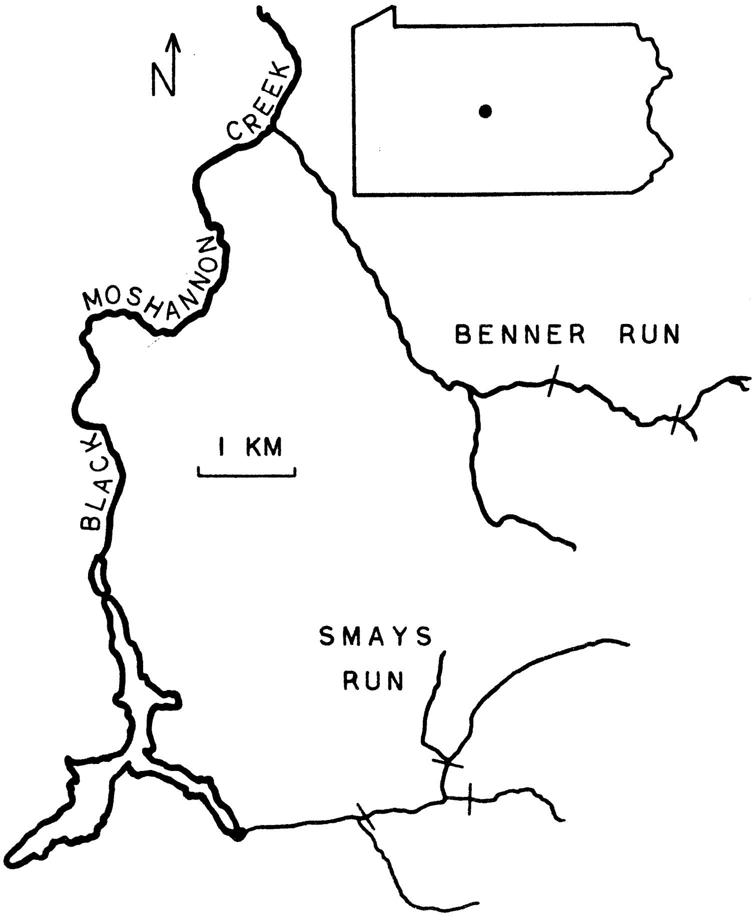

Figure 1.—Map of Benner Run and Smays Run, Pennsylvania, study streams. Tick marks delimit the study areas.

the Pennsylvanian period. The area receives about 112 cm of rainfall annually, and although they can fluctuate radically with heavy rains, stream flows in the headwaters are relatively stable (Appendix A). Summer water temperature rarely exceeds 20 C (Appendix A) because of groundwater inflow and shading. The study area is within the Black Moshannon State Forest, and only a few hunting camps are present. Vehicular access is limited to an unimproved dirt road (impassable in winter) crossing the headwaters.

Benner Run is 6.7 km long, has a gradient of 21.8 m/km, and drains 16.7 km^2. Channel width averages 2.7 m in the headwaters and 4.2 m near the mouth. The 1.7 km long study area in the headwaters has an average width of 2.7 m and 18.3 m/km gradient. The substrate is composed of rubble and gravel with much sand, particularly in the headwaters. Values of pH, total alkalinity, and specific conductance on 3 February 1978 were 6.4 units, 3 mg/liter as $CaCO_3$, and 15 μmhos cm^{-1}, respectively. Only slimy sculpins (Cottus cognatus) and wild brook trout inhabit the upper reaches (only two brown trout have ever been taken), but brown trout dominate the lower half of the stream.

Smays Run is 4.6 km long and drains 7.7 km^2. The study area, located in the headwaters, had a 8.0 m/km gradient and average width of 4 m. The substrate is similar to Benner Run. Total alkalinity, pH, and specific conductance on 19 October 1978 were 11 mg/liter, 6.9 units, and 30 μmhos cm^{-1}, respectively. The fish populations are dominated by brook trout and slimy sculpins. The lower reach flows through a swamp before entering Black Moshannon Lake. The lake probably prevents immigration of brown trout and accounts for the presence of a few creek chubs (Semotilus atromaculatus) and a brown bullhead (Ictalurus nebulosus) in the study area.

MATERIALS AND METHODS

Trout Population Estimates

Petersen population estimates were calculated for October 1975 and 1978 to assess standing stock, age structure, and potential egg deposition of brook trout in the study sections of Benner and Smays Run. Fish were collected with a high-voltage, alternating current electrofisher. Population number was estimated for 50-mm size groups from formula 3.7 and confidence limits were calculated from Appendix II of Ricker (1975). Scale samples were taken and weights recorded from up to 30 fish in each size group. Scales were aged by use of a microprojector, and age structure was determined from age composition of the catch in each size group. Population estimates were apportioned between ages based on the percent of each age within a size group (Ketchen 1949; Ricker 1975). Estimates of egg deposition were based on the sex ratio and fecundity relationships reported by Wydoski and Cooper (1966) for similar infertile Pennsylvania streams.

Selection of Study Redds

Redds of wild brook trout were identified in October 1975 and 1977, during the peak of spawning by their location, silt-free and algal-free tailspills, unconsolidated gravel substrate, and, occasionally, by the presence of a female trout digging a redd. I gained experience in streams other than those studied by excavating suspected spawning sites and finding eggs.

A total of 36 natural brook trout redds was selected for study, five of which subsequently proved to be "false" redds. Although false redds appeared normal, no eggs or alevins were found when they were excavated. Such redds were known to occur in these streams (E. L. Cooper personal communication[2]), but I could not be certain if a redd contained eggs without excavating it. Moring and Lantz (1975) found 14.5% of the coho salmon (Oncorhynchus kisutch) redds they studied did not contain embryos or alevins and felt gravel scouring had removed the embryos or alevins. However, I found no evidence of gravel scouring in my study redds.

Obviously, false redds could not be used in investigating the relation of survival to environmental factors. However, measurements of the chemical and physical character of these redds are reported here because these data were considered useful in characterizing the intragravel environment. It was also possible that these redds may have contained embryos or alevins that died and completely decayed before excavation, or, for other reasons, sampling may have failed to recover them. Some brook trout in these streams mature at a small size and, consequently, produce relatively few eggs (Wydoski and Cooper 1966). When only a few eggs were present in a redd, sampling error could have been significant.

In addition to the wild or natural redds, five artificial redds, each with a known number of eggs, were constructed in each stream at sites judged suitable for spawning. On 28 October 1977, hatchery brook trout eggs were stripped and fertilized and 100 eggs siphoned to about 10 cm below the gravel surface in each artificial redd. A net placed

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[2]E. L. Cooper, Professor of Zoology, Pennsylvania State University, University Park, PA.

downstream caught any eggs lost in the process, and the losses were substracted from the total number planted.

The natural redds and 10 artificial redds were divided between embryo survival and emergence study groups (Table 1). Redds in the embryo survival group were monitored for dissolved oxygen until winter (December-January) when embryos had developed to the eyed stage; at that time redds were excavated, survival determined, and substrate analyzed. Redds in the emergence study group had fry traps placed over them in January. Dissolved oxygen was monitored until substrate sampling and excavation in spring (March-April). Estimates of both embryo survival to eyed eggs stage and emergence were obtained from the artificial redds because all ten were excavated in winter and four were replanted with live eyed embryos and reexcavated in spring.

Monitoring Intragravel Water

Standpipes, driven in the center of each redd, were used to monitor dissolved oxygen and temperature of the intragravel water. In 1975 single 13-mm inside diameter PVC (polyvinyl chloride) standpipes were used. In 1977-1978 two 19-mm inside diameter standpipes, spaced 20 cm apart parallel to stream flow, were driven near the center of each redd. The lower 7.5-cm section of all standpipes was perforated with twenty-eight 3-mm holes and twenty-eight 2-mm holes spaced evenly about the circumference. Standpipes were driven to a depth of 15 cm; water and sediment pumped out; the top of the pipe, which extended above the water, closed with a cork; and a handful of sand was poured around the pipe where it emerged from the gravel.

Surface water temperature outside the standpipe and intragravel water temperature at the bottom of the pipe were measured with a mercury

Table 1.—Type and number of brook trout redds studied in Benner Run 1975-1976 and 1977-1978 and Smays Run 1977-1978.

Stream and Year	Type of Redd	Redds Excavated in Winter[a] ("false" redds[b])	Redds Excavated in Spring[c] ("false" redds[b])
Benner Run			
1975-1976	Natural	14 (2)	0
1977-1978	Natural	4 (1)	3 (1)
	Artificial	5	2
Smays Run			
1977-1978	Natural	12 (0)	3 (1)
	Artificial	5	2

[a]Redds excavated in December and January to estimate survival of embryos to eyed stage.

[b]No evidence of eggs or alevins found.

[c]Redds with fry traps placed over them in January to estimate emergence and excavated in March and April.

thermometer (1975) or a thermistor probe and meter (1977 and 1978). Dissolved oxygen concentration of stream surface and intragravel water was measured with a semimicro modification of the Winkler method. I used procedures similar to those described by Harper (1953) and McNeil (1962). Small bore tubing was lowered to the bottom of the standpipe and a 30-ml (approximately) water sample withdrawn by suction into a sample vial (Fig. 2). Samples were fixed in the field and returned to a laboratory for titration. Each sample was acidified, and a 25-ml subsample, measured with a volumetric flask, was titrated with phenylarsine oxide (PAO) over a magnetic stirrer (U. S. EPA 1974). A 5-ml buret graduated to 0.01 ml was used to dispense titrant.

On 1 November 1975 standpipes were driven in redds in Benner Run and sampling began the next day. In 1977 standpipes were driven in all redds on 24 October, and measurements began on 29 October in Smays Run and 30 October in Benner Run. In both years, monitoring of intragravel dissolved oxygen and temperature continued weekly or biweekly (depending on the number of samples and weather) until redds were excavated.

In addition to standpipes in the center of each redd, transects were established across natural redds to study site selection. With the redd as center, transects were established both parallel and perpendicular to stream flow and standpipes were driven every 20 cm (Fig. 3). After at least 24 hours had elapsed, I measured temperature, dissolved oxygen concentration, and pH of stream and intragravel water. The pH was measured with a Beckman Electromate meter or a Hellige narrow range comparator. Measurements of all Benner Run redds were made between 13 and 18 November 1977. The 10 Smays Run redds were measured between 20 November and 16 December 1977. (Because of the large number of

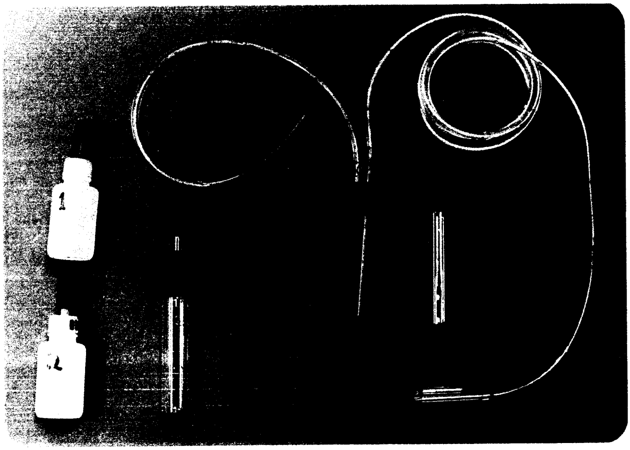

Figure 2. —Apparatus for withdrawing water samples from standpipes and fixing dissolved oxygen for later analysis in a laboratory.

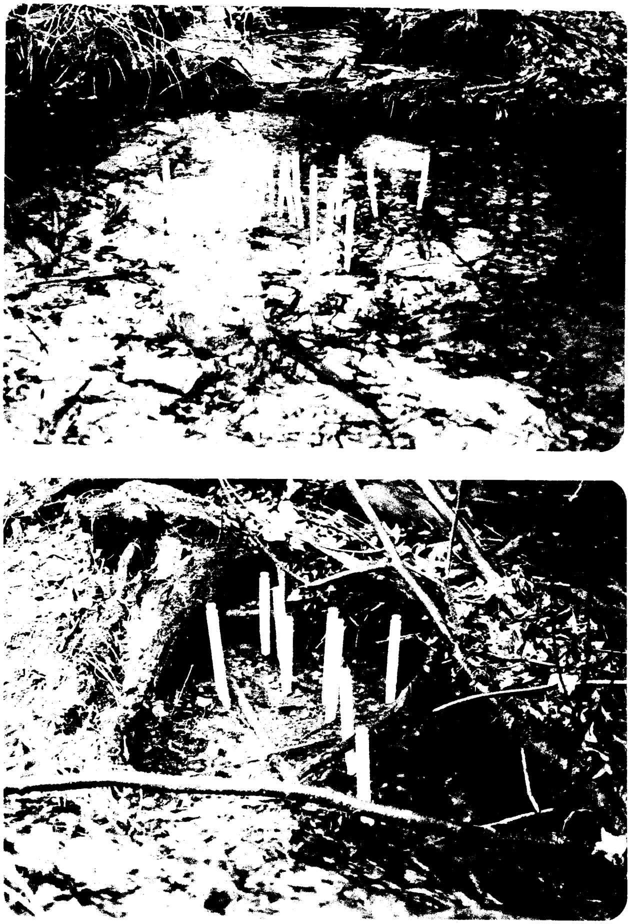

Figure 3.—Standpipes, 20 cm apart, set on transects across center of brook trout redds.

standpipes required, all redds could not be sampled on the same day). Transects across three redds in Smays Run were resampled about 25 days after initial measurements.

Excavation of Redds

Redds were excavated when embryos were near hatching. Developmental temperature units (TU) were calculated from average stream water temperatures and hatching dates of eggs estimated (800 TU or 70 days) (Embody 1934; Leitritz and Lewis 1976). The midpoint of the temperature range recorded by maximum-minimum thermometers anchored just above the stream bed was used to estimate the average weekly or biweekly temperature (Macan 1958).

Redds were excavated with a 15-cm diameter core sampler, eggs were separated on a 2-mm mesh sieve, and all eggs and alevins counted. The sampler, Fig. 4, consisted of a 15-cm diameter cylinder surrounded by an outer conical collection basin; it was similar to that developed by McNeil and Ahnell (1964). The sampler took an average of 2.8 kg of substrate from each redd; samples varied from 0.5 to 6.3 kg. After withdrawing the sampler, I continued to excavate the redd with a hand trowel and egg-picking pipet to recover any remaining eggs. Eggs and alevins dislodged were caught by a fine mesh net held immediately downstream during sampling and excavation. Each substrate sample was washed through a 2-mm mesh brass sieve. Water and substrate passing the sieve were collected in a container. The materials retained on the sieve were examined for eggs and alevins. Eggs, alevins, and fragments were counted and preserved and later counted again in the laboratory. The two portions of substrate sample were recombined and allowed to settle before the clear water was decanted. A row of eggs from each

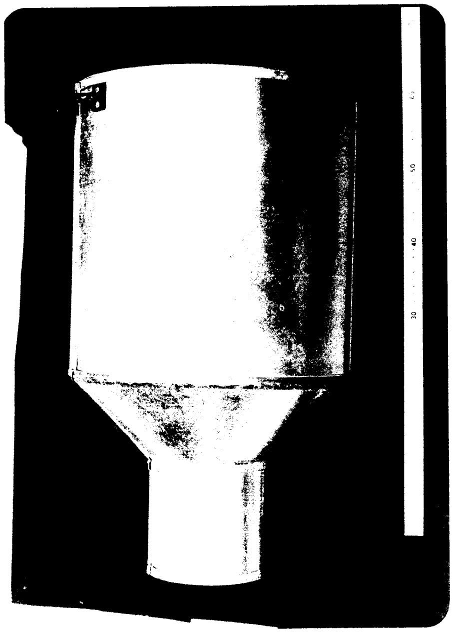

Figure 4.—Core sampler used to take substrate sample from redds.

redd was measured, and the total length divided by the number of eggs gave average diameter per egg (Vladykov and Legendre 1940).

Estimating Embryo Survival

Survival to eyed egg stage was estimated from the ratio of the number of eyed embryos found to the total number of embryos found with correction for decay and loss of dead embryos.

For the purpose of this study, survival was defined as development to a stage where the eyes were visible, regardless of whether the embryo (or alevin) was alive or dead at the time of excavation of the redd.

The rate of disappearance of dead embryos in redds was estimated from the decay and loss of known numbers of brook trout eggs in plastic mesh sacks buried in Benner Run. Sacks of plastic window screen (7 mesh/cm) each containing 50 hatchery brook trout eggs were buried near the maximum-minimum thermometer in October. In 1975 all eggs were unfertilized; in 1977 embryos in fertilized eggs were killed by rapping the egg sacks against a concrete floor. Egg sacks were removed from the stream bed at intervals throughout the study and whole eggs and egg pieces counted.

A least squares predictive regression of percent loss of eggs in mesh sacks over time was used to estimate the numbers of eggs originally present in natural redds from those found at excavation. Deposition of wild eggs in natural redds was assumed to have occurred on 20 October 1975 and 10 October 1977 in Benner and Smays Runs. When egg pieces were found in redds, two pieces were arbitrarily equated to one whole egg rounded up to the next whole number.

Substrate Analysis

Substrate composition was determined using a series of eight 20-cm diameter U. S. Standard brass sieves with square mesh openings of 64, 32, 8, 2, 0.5, 0.25, 0.125, and 0.063 mm. The oven dry (100 C for 24 hours) contents of each sieve and the silt and clay were weighed on a top-loading analytical balance to the nearest gram. The 1975 samples were oven dried, then sieved by a roto-tap shaker for 10 minutes. Because a mechanical shaker was not available in 1978, I wet sieved the samples by repeatedly washing the sieves while shaking them by hand with final separation achieved by puddling. All water and substrate materials were collected, the water evaporated, and the contents oven dried.

Cumulative percent coarser (abscissa) and phi units (ordinate) were plotted for each redd on arithmetic probability paper. The resultant graph was used to calculate mean particle size of the substrate (King 1966; Mundie 1970; Platts et al. 1979; Shirazi and Seim 1979). The phi (ϕ) scale converts the sieve sizes of the geometric Wentworth scale to an arithmetic scale of equal class interval where phi is $-\log_2$ of the particle size in millimeters.

A modified mean (Folk and Ward 1957) was used to describe the central tendency of substrate particle size for each redd. The mean was calculated according to the formula:

$$\text{Mean } \phi = (\phi16 + \phi50 + \phi84)/3$$

where $\phi16$, $\phi50$, and $\phi84$ are the particle sizes in phi units read from the cumulative frequency curves at 16, 50, and 84%, respectively.

The mean ϕ has an efficiency of 88% and yields an arithmetic mean particle size in phi units or a geometric mean when converted to millimeters (King 1966).

Each substrate sample collected in 1975 was analyzed for organic matter and permeability. Coefficient of permeability, the ability of the substrate to transmit water, was measured in a constant head permeameter of 78.6 cm^2 cross sectional area following the procedures and calculations of McNeil and Ahnell (1964). Organic matter content of the silt/clay fraction (<0.063 mm) was determined by the ash-free dry weight method (Weber 1973).

Estimating Emergence

At the end of January 1978, after excavation of other redds, fry traps (Fig. 5) were placed over 10 of the study redds to estimate emergence. Traps were placed over three natural redds and two artificial redds in each stream. Natural redds were not excavated until the end of the emergence study. Artificial redds were excavated at the eyed egg stage, then replanted with known numbers of live eyed embryos taken from other natural and artificial redds. The majority of the embryos replanted were from wild stock. Dissolved oxygen monitoring was continued through single standpipes. The fry traps were smaller versions of those described by Porter (1973) to accommodate smaller fish and streams and to reduce weight (Appendix B). Disappearance of dead alevins from trapped redds was estimated from the loss of known numbers of dead alevins in mesh sacks buried in Benner Run. Nine sacks were buried in the stream bed on 30 December 1977 and 13 sacks on 14 January 1978. Each sack contained 50 hatchery brook trout alevins at the swim-up stage. Alevins were killed by freezing just before planting. Sacks were retrieved at approximately two-week intervals between burial and 30 April 1978.

Figure 5.—Fry traps in place over brook trout redds.

RESULTS AND DISCUSSION

Brook Trout Populations

Benner Run standing stock estimates in 1975 and 1978 averaged 58 kg/hectare and 6,067 trout/hectare (Table 2). Size and age structure of the population were similar in both samples. The estimated standing stock in the Smays Run study section in 1978 was 60 kg/hectare and 4,507 trout/hectare (Table 2). Smays Run brook trout were consistently larger at each age than those in Benner Run (Table 3).

Wild brook trout in Benner Run produced an estimated 43,150 eggs/hectare in 1975 and 62,942 in 1978. In 1978 egg production in Smays Run was estimated at 53,463 eggs/hectare (Table 3). Young fish accounted for the bulk of the egg production. Age I and II females contributed an average of 63% of the total number of eggs. The abundance of these young spawners more than compensated for the smaller egg complement per female. About 25% of the trout in Benner Run and 39% of those in Smays Run were young-of-the-year (YOY). During the two years, numbers of YOY brook trout in Benner Run ranged between 1,299 and 1,737 fish/hectare. Smays Run had an estimated 1,743 YOY/hectare in October 1978.

Survival of brook trout from egg to fall fingerling was estimated to be 3%. An estimated average of 53,046 eggs/hectare was deposited in Benner Run and 1,518 YOY/hectare survival to October, thus mortality was approximately 97%. Only one population estimate was made in Smays Run, but if a stable population was assumed, an estimated 53,463 eggs/hectare

Table 2. —Population estimates of wild brook trout in the study sections of Benner Run 1975 and 1978 and Smays Run 1978.

Stream, Sample Date, and Surface Area	Size Class (mm)	Marked	Captured	Recapture	Population Estimates	Mean Weight (g)	Fish/ Hectare	Kg/ Hectare	Age Composition by Size Class: Age	Age Composition by Size Class: Percent	Age Structure: Age	Age Structure: Fish/ha	Age Structure: Percent
Benner Run	25- 99	156	115	31	569	4.5	3,092	13.9	O	42	O	1,299	24
									I	58			
16 Oct 1975											I	2,383	45
	100-149	130	91	29	402	15.5	2,185	33.9	I	27	II	1,311	24
									II	60			
0.184 hectare									III	13	III	322	6
	150-199	6	5	5	14	32.8	76	2.9	III	50	IV	38	1
									IV	50			
Total		292	211	62	985	-	5,353	51	-	-	-	5,353	100
Benner Run	25- 99	228	219	102	489	4.2	3,776	15.9	O	46	O	1,737	26
									I	54			
6 Oct 1978											I	2,239	33
	100-149	190	179	92	370	15.3	2,857	43.7	I	7			
									II	87	II	2,514	37
0.13 hectare									III	6	III	216	3
	150-199	10	11	6	19	35.3	147	5.2	II	20			
									III	30	IV	59	1
									IV	40			
									V	10	V	15	0
Total		428	409	200	878	-	6,780	65	-	-	-	6,780	100
Smays Run	25- 99	150	82	44	279	3.7	2,051	7.6	O	85	O	1,743	39
									I	15			
18 Oct 1978											I	1,803	40
	100-149	116	90	40	260	14.4	1,912	27.5	I	77			
									II	23	II	668	15
0.136 hectare	150-249	48	38	25	74	44.9	544	24.4	I	4	III	228	5
									II	42			
									III	42	IV	65	1
									IV	12			
Total		314	210	109	613	-	4,507	60	-	-	-	4,507	100

Table 3.—Estimated egg production by wild brook trout in Benner Run October 1975 and 1978 and October 1978 in Smays Run.

Stream	Age	Mean Length[a]	Eggs/♀[b]	♀/Hectare[c]	% ♀ Mature	Mature ♀/ Hectare	Eggs/Hectare	% of Total
Benner Run	1+	98 mm	23	1,188	17.2	204	4,700	10.9
	2+	124	49	655	69.4	454	22,274	51.6
1975	3+	148	86	166	100.0	166	14,276	33.1
	4+	155	100	19	100.0	19	1,900	4.4
						843	43,150	100.0
Benner Run	1+	93 mm	19	1,112	17.2	191	3,634	5.8
	2+	125	50	1,255	69.4	871	43,549	69.2
1978	3+	153	96	116	100.0	116	11,136	17.7
	4+	161	113	31	100.0	31	3,503	5.6
	5+	172	140	8	100.0	8	1,120	1.8
						1,217	62,942	100.1
Smays Run	1+	110 mm	33	897	17.2	154	5,091	9.4
	2+	152	94	338	69.4	234	22,050	41.2
	3+	176	151	114	100.0	114	17,214	32.2
	4+	212	276	33	100.0	33	9,108	17.0
						535	53,463	99.9

[a] In October.

[b] Estimated % mature and eggs/female from Wydoski and Cooper 1966.

[c] Sex ratio assumed 1:1.

were deposited and 1,743 YOY/hectare survived to the fall for a 97% mortality for the period. A survival rate of 3% from egg deposition to fall fingerling is within the 2 to 16% range of survival rates reported for the species (Smith 1947; Cooper 1953; McFadden 1961; Shetter 1961; McFadden et al. 1967).

Site Selection

Brook trout dug redds in a variety of locations: shallow riffles in the thalweg, the bottom of deep (one meter) pools, and near the bank in eddies and slack backwaters covered by only a few centimeters of water. Redds were usually solitary although occasionally a pair occurred in close proximity, and they were not uniformly distributed along the length of a stream.

Many redds were located immediately upstream of an abrupt transition or break in the stream bed profile, such as the lip of a small pool, in front of a buried log or limb (Fig. 6), or where a short, fast riffle broke into a pool. Hazzard (1932) found brook trout redds at the foot of pools where the water broke, and Reiser and Wesche (1977) also noted redds immediately upstream of logs. These locations appear similar to areas of downwelling used by brown trout for spawning (Stuart 1953a, 1953b, 1954). Brook trout are generally considered to prefer upwelling groundwater for spawning under natural conditions (Benson 1953; White 1930; Griswold 1967) and in artificial and laboratory situations (Webster and Eiriksdottir 1976). However, because I did not measure flow or pressure differential of intragravel water in the field, the presence of upwelling or downwelling could not be confirmed.

Individual redds were usually about 15 cm in diameter and contained little silt or sediment. Substrate of redds was always loose or

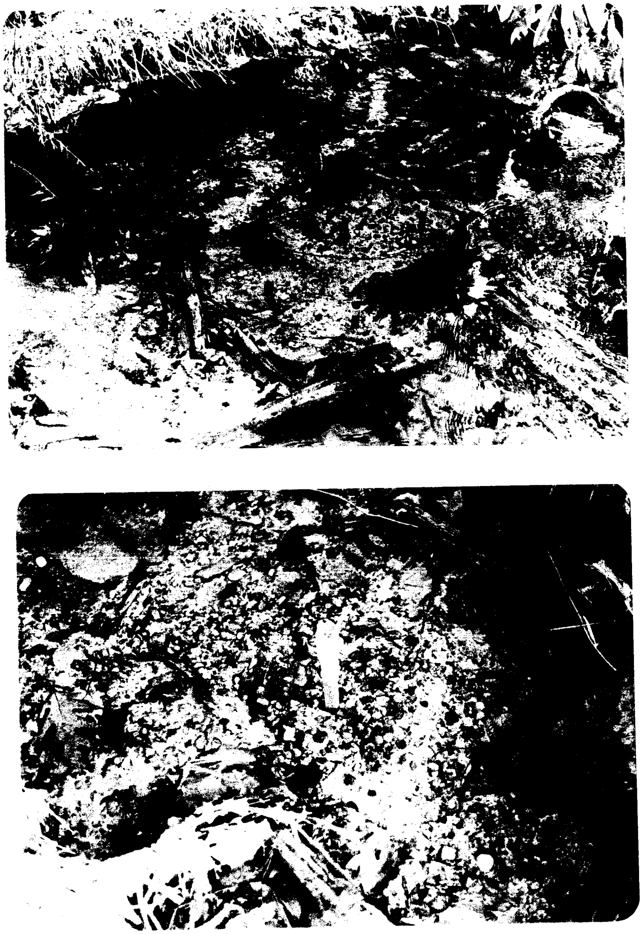

Figure 6.—Brook trout redds at downstream edge of a pool and immediately upstream of buried limbs or logs.

unconsolidated compared to adjacent areas, and redd sites were characterized by the ease with which a hand trowel penetrated the substrate. Redds were shallow, roughly 5 to 10 cm deep. The hard rocky stream bed and small size of the fish probably limited the sites selected and the depth of the redds. It was usually difficult to drive standpipes deeper than 15 to 20 cm into the substrate. In Wyoming, Reiser and Wesche (1977) reported the deepest redd they found was 8 cm for brook trout and 16 cm for brown trout. Hobbs (1937) found that redds of brown trout in New Zealand were between 15 and 25 cm deep with most being 20 cm deep.

I found several redds where the egg pockets were located in a gap between two cobbles or in a shallow gravel layer underlain by hardpan. Needham (1961) noted similar locations. I also saw a female deposit eggs in the cracks of a small log. The log was buried slightly below the surface of the stream bed and some of the wood layers had decayed, leaving deep crevices.

Intragravel dissolved oxygen, measured on transects, did not elucidate the sites selected for redds because point samples were highly variable and could not be interpreted without knowledge of subsurface gravel composition and permeability. I did not gather enough evidence to detect a difference between dissolved oxygen concentrations in redds and those of locations immediately upstream, downstream, left, and right of the redds ($F = 2.02$, $df = 4,214$). Except for three observations, intragravel water had less dissolved oxygen than surface water, and redds were not located consistently in areas of highest dissolved oxygen. Transects remeasured about 25 days after the initial measurements were made often produced complete reversal of trends and point concentrations of dissolved oxygen.

Intragravel water temperatures were generally uniform along transects, rarely differing by more than 0.2 C. Intragravel temperatures were often lower than surface waters. In one instance, temperatures 0.2 to 0.5 C higher than the surface probably reflected a time lag in reaching equilibrium after several days of warm rains. There was little evidence that redds were located in areas warmed by groundwater as found by White (1930), Benson (1953), and Hunt (personal communication[1]).

Water Temperature

Average intragravel water temperature in redds was about 9 C in October; it declined to less than 4 C in winter, then rose in March to 7 C (Figs. 7, 8, and 9). Stream and intragravel water temperatures measured on the same date were almost identical and followed the same temporal pattern; therefore, there was little evidence that warmer groundwater influenced the temperature of brook trout redds.

Temperatures were well within the requirements for all phases of brook trout reproduction. Except for two instances in autumn 1975, maximum stream water temperature was well below 12 C during the study. Redd temperatures rarely exceeded 9 C but might have been higher for brief periods because intragravel water temperatures closely followed stream temperatures. Temperature less than 12 C is needed for spawning with less than 9 C necessary for optimal spawning behavior, viability of eggs and sperm, and survival of fertilized eggs (Hokanson et al. 1973). For successful hatching and survival of alevins, temperatures should be less than 20 C and average less than 16 C (McCormick et al. 1972).

Temperatures of 0 C and less were recorded by maximum-minimum thermometers in Benner and Smays Runs in January 1976 and February and March 1978 (Appendix A). However, it was not known if freezing

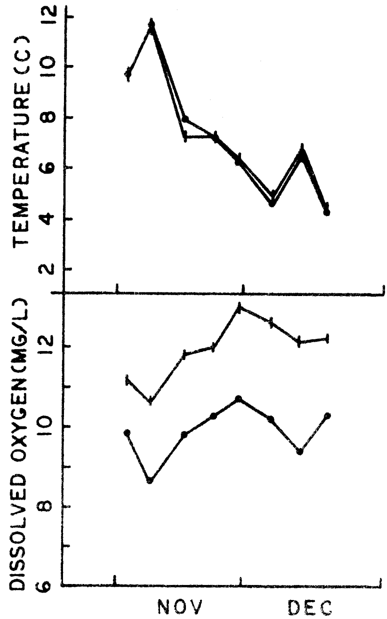

Figure 7.—Benner Run, 1975, temperature and dissolved oxygen content of stream surface water (—+—) and intragravel water (—●—) in redds. Points plotted for redds are means for each sampling date.

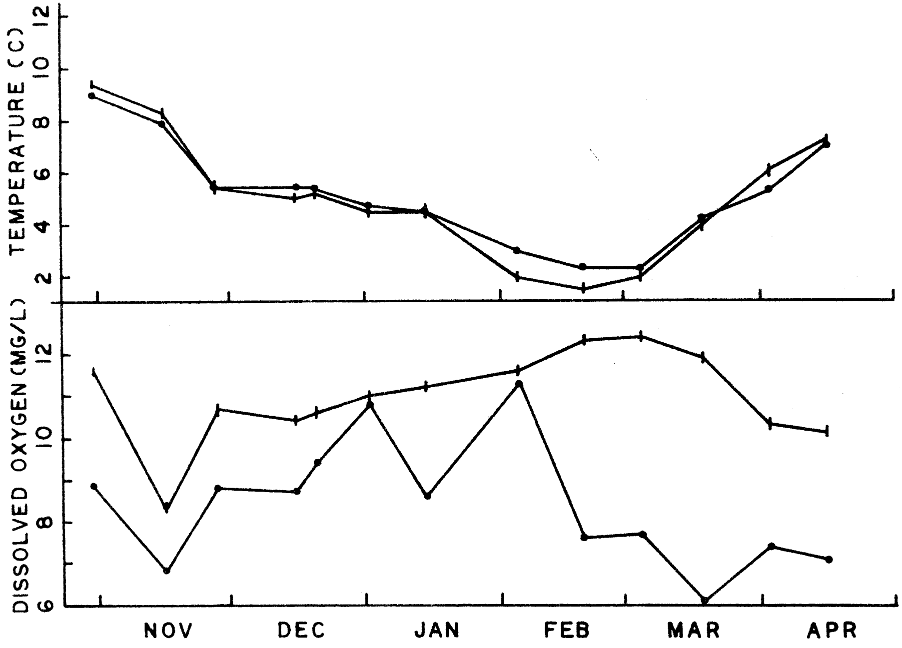

Figure 8. —Benner Run, 1977-1978, temperature and dissolved oxygen content of stream surface water (—┼—) and intragravel water (—●—) in redds. Points plotted for redds are means for each sampling date.

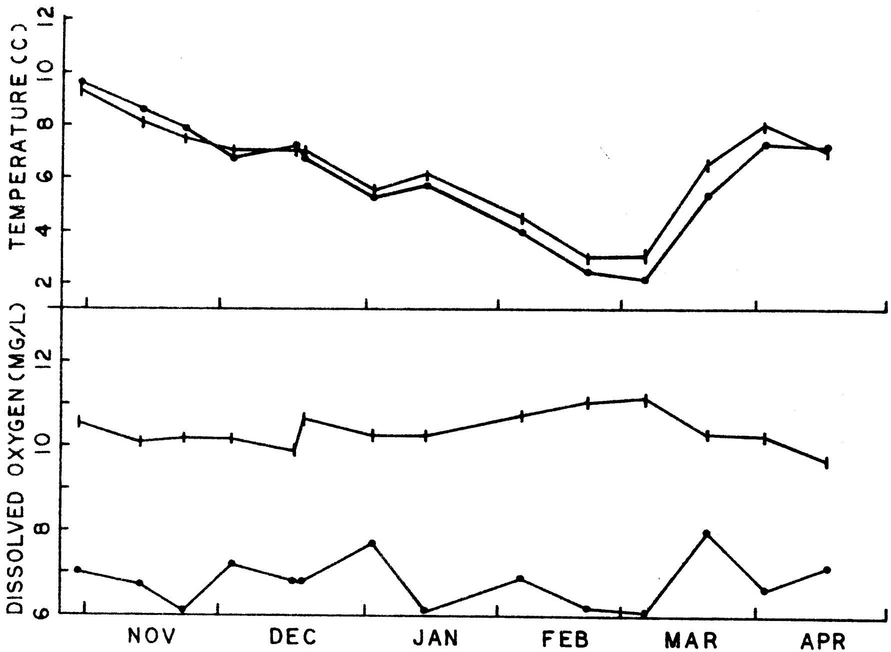

Figure 9.—Smays Run, 1977-1978, temperature and dissolved oxygen concentrations of stream surface water (—┼—) and intragravel water (—●—) in redds. Points plotted redds represent means for all redds sampled each date.

temperatures occurred in redds. In Wyoming, Reiser and Wesche (1977; 1979) found high mortality of brown trout eggs in artificial redds that had freezing water, and some redds actually froze. White (1965) also observed high mortality in natural brook trout redds with 0 C temperature. However, because of the higher altitude and colder weather in those studies, temperature was probably 0 C for longer periods than in Benner and Smays Runs.

Hydrogen Ion Concentration

Acid precipitation appeared to influence the study streams because pH of surface and intragravel water was reduced after several days of heavy rains. A winter rainstorm began on 6 November 1977 and continued for three days. On 8 November, Benner Run and Smays Run had a pH of 4.5 and 5.5, respectively. High flows overtopped standpipes and prevented my sampling of intragravel water. On 17 November, Benner Run surface water pH was 4.2 and total alkalinity was 0 mg/liter, while pH in redds ranged from 5.2 to 5.6. On 19 November, Smays Run pH was 6.2 and total alkalinity 6 mg/liter. The next day pH in redds ranged from 5.4 to 6.7 and surface water pH was 6.7. Hydrogen ion concentration was probably greater in Benner Run because there was little or no buffering capacity to resist pH shifts. Reduction in pH following rain has been documented in similar streams (Dunson and Martin 1973; Arnold personal communication[3]; Hollender unpublished).

Developing brook trout embryos in the study streams were subjected to pH 5.5 and possibly as low as pH 4.5, which verge on lethal limits. Since intragravel water quality followed that of the surface water, pH

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[3] D. E. Arnold, Pennsylvania Cooperative Fishery Research Unit, University Park, PA.

in redds may have declined as low as pH in the stream. Laboratory studies of brook trout (Trojnar 1977) and brown trout (Carrick 1979) embryos incubated in acidified water have shown decreased survival at about pH 4.5. Spawning female brook trout have been found to be able to detect pH of upwelling water and avoid pH 4.0 to 4.5 and cease digging redds if pH remains below 5.0 (Johnson 1975).

Dissolved Oxygen

The grand average (mean of means) dissolved oxygen concentration in 36 natural brook trout redds was 8.2 mg/liter, but dissolved oxygen concentrations in many redds were probably low enough to impair development of embryos. The range of means was 3.7 to 11.6 mg/liter. About one quarter of the redds had mean dissolved oxygen concentrations less than 6 mg/liter and seven redds experienced point values of 3.0 mg/liter or less (Table 4; Appendix C). Laboratory studies have demonstrated that salmonid embryos can survive concentrations of 2 to 3 mg/liter, but growth and developmental rates were reduced and deformities increased at these concentrations. Below 2 mg/liter extensive mortalities occurred (Silver et al. 1963; Shumway et al. 1964; Garside 1966; Carlson and Siefert 1974; Siefert and Spoor 1974). However, Alderdice et al. (1958) found chum salmon (*Oncorhynchus keta*) embryos held for seven days at 0.7 and 1.8 mg/liter dissolved oxygen concentrations survived if concentrations returned to near saturation for the remainder of the incubation period.

Dissolved oxygen in intragravel water of redds varied between streams and years. Dissolved oxygen in natural redds was highest in Benner Run 1975-1976, grand average 9.9 mg/liter, and lowest in Smays

Table 4.—Intragravel dissolved oxygen (mg/liter) in study redds (Appendix C).

BENNER RUN 1975-1976			BENNER RUN 1977-1978			SMAYS RUN 1977-1978		
Redd[a]	Mean	Minimum	Redd[a]	Mean	Minimum	Redd[a]	Mean	Minimum
1	5.9	4.2	1	8.8	5.4	1	7.8	3.1
2	10.4	8.2	(2)	9.7	7.1	2*	6.8	4.3
3	11.3	10.0	3	7.1	3.9	3	8.3	7.1
4	10.2	8.8	4*	8.9	5.5	4*	8.4	6.0
5	8.3	6.2	5	5.7	3.0	5	9.9	7.8
6	7.8	7.0	6*	10.5	7.1	6	3.7	0.6
7	11.1	9.6	(7)*	5.6	1.6	7	7.1	2.5
(8)	7.7	4.8	A	10.1	9.5	8	7.3	1.8
(9)	11.5	10.2	B*	9.6	8.0	9	6.9	3.4
10	10.1	6.0	C	9.0	8.5	10	4.6	1.6
11	10.1	8.2	D*	9.2	5.1	11	5.6	2.0
12	11.2	10.1	E	10.8	10.3	(12)*	6.3	3.1
13	11.5	10.2	Stream	10.9	9.0	13	6.5	3.6
14	11.6	10.3				14	6.0	4.3
Stream	12.0	10.5				15	6.5	2.9
						A	4.5	2.9
						B	8.8	7.3
						C*	3.2	1.3
						D*	6.9	2.7
						E	6.5	2.4
						Stream	10.4	8.0

[a]Numerals denote natural (wild) redds, letters denote artificial redds.

*Redd over which a fry trap was placed.

( )Redd in which no evidence of embryos or alevins was found.

Run 1977-1978, grand average 6.7 mg/liter. The average of Benner Run redds in 1977-1978 was 8.1 mg/liter. In 1977-1978 artificial redds in Benner Run and Smays Run averaged 9.7 mg/liter and 6.0 mg/liter, respectively.

Surface water dissolved oxygen averaged more than 10 mg/liter and was always above 8 mg/liter (Appendix C). Dissolved oxygen levels rose as stream temperatures in Benner Run fell, but this trend was not as pronounced in Smays Run where surface water dissolved oxygen remained relatively constant (Figs. 7, 8, and 9).

Mean dissolved oxygen in redds was lower than, but tended to follow, surface water concentrations. In 1975-1976 dissolved oxygen in Benner Run redds averaged 2.1 mg/liter less than the surface water. In 1977-1978 Benner Run redds contained about 2.8 mg/liter less dissolved oxygen than surface water. In Smays Run intragravel dissolved oxygen was lower than Benner Run and fluctuated less. Smays Run redds contained about 3.7 mg/liter less dissolved oxygen than the surface water.

Some of the apparent variation observed in both streams in 1977-1978 may have been the result of small sample size. During cold winter weather and decreasing flows, water inside standpipes froze. When measurements were made, ice was removed with a propane torch and long pointed steel rod. Sometimes the ice was so thick that samples could not be taken from all redds. The 11.3 mg/liter concentration in Benner Run on 4 February 1978 (Fig. 8) represents only one redd.

I am unaware of other investigators who monitored dissolved oxygen in wild brook trout redds throughout the incubation period. However, Hausle and Coble's (1976) observations of dissolved oxygen in artificial brook trout redds were similar to my artificial redds, and Hansen's

(1975) dissolved oxygen measurements in wild brown trout redds were comparable to those of wild brook trout that I studied. Hausle and Coble (1976) built artificial redds in Lawrence Creek, Wisconsin. The mean dissolved oxygen concentration in seven redds was 7.1 mg/liter (n = 47), and concentrations less than 6.5 mg/liter were never observed. In my study, 10 artificial redds averaged 7.9 mg/liter, but 5 redds had minimum concentrations less than 6.0 mg/liter. Hansen (1975) presented 56 dissolved oxygen measurements taken in wild brown trout redds when stream water temperature was 0 C. Redd temperatures ranged from 0 to 7.5 C, while dissolved oxygen was 1.5 to 12.5 mg/liter.

Redd Substrate Composition

Wild brook trout spawned in fine gravel with geometric mean (GM) particle size in individual redds ranging from 0.6 mm coarse sand to 14.2 mm gravel (Appendix D). The grand average GM particle size of 35 natural redds was -1.72ϕ or 3.3 mm. Average GM particle size of redd substrate was 2.5 mm, 3.0 mm, and 4.4 mm for Benner Run 1975-1976, 1977-1978, and Smays Run 1977-1978, respectively. Particle size distribution of substrate in redds was similar between streams and years (Fig. 10). Substrate composition of 10 artificial redds was similar to natural redds. Average GM particle size of artificial redds was 2.3 mm (-1.23ϕ) and was not significantly different ($t = 0.772$, $df = 43$) from natural redds.

Substrate in most natural redds was predominantly gravels and sands retained by the 8-mm thru 0.25-mm sieves with little material coarser or finer (Table 5). Redds contained no cobbles (≥64 mm) and little silt or clay. Silt and clay ranged from 0.3 to 2.7% by weight and averaged

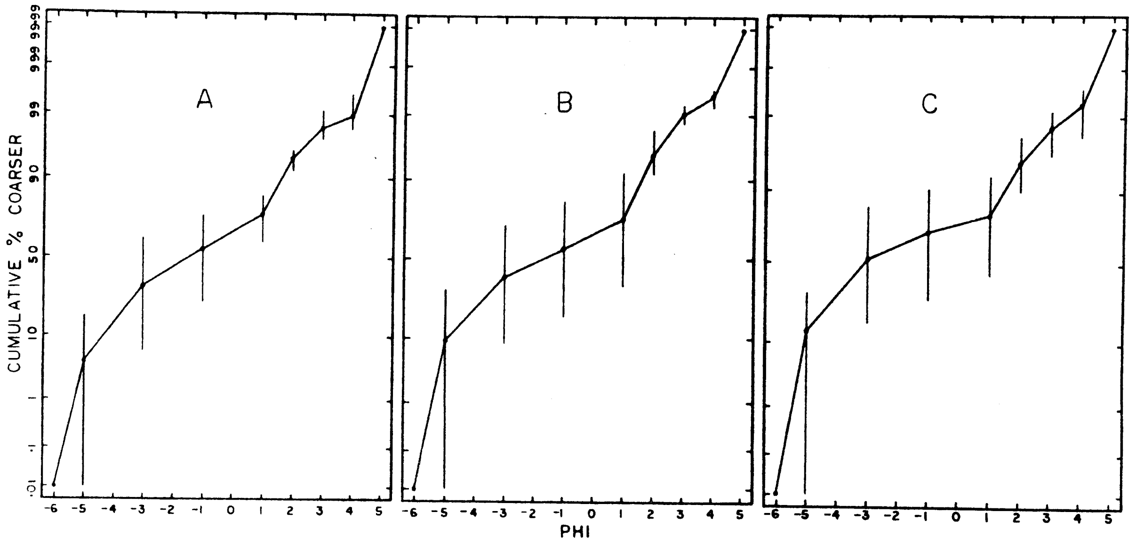

Figure 10.—Substrate particle size distribution of (A) 14 brook trout redds in Benner Run 1975-1976, (B) 8 brook trout redds in Benner Run 1977-1978, and (C) 15 brook trout redds in Smays Run 1977-1978. Circles denote means and vertical bars ranges.

Table 5.—Particle size composition of brook trout redds determined by sieve analysis of core samples. Analyses presented as mean percentage of weight retained by each sieve in the series.

Sieve Series Particle Size		BENNER RUN 1975-1976		BENNER RUN 1977-1978		SMAYS RUN 1977-1978	
Ø	mm	Mean %	Range	Mean %	Range	Mean %	Range
		14 Natural Redds		7 Natural Redds		15 Natural Redds	
-6	64	0.0	-	0.0	-	0.0	-
-5	32	4.8	0-17	9.4	0-32	13.6	0-31
-3	8	27.1	5-43	30.1	9-54	38.0	12-55
-1	2	23.5	17-32	17.8	8-34	16.4	7-25
1	0.5	20.4	9-37	17.4	5-36	9.7	3-16
2	0.25	18.6	10-35	21.0	6-58	16.5	5-45
3	0.125	3.7	3-5	3.4	1-4	4.2	1-10
4	0.063	0.8	0.5-1.3	0.5	0.3-0.8	1.0	0.5-2.1
5	Silt-Clay	1.0	0.4-1.6	0.4	0.3-0.6	0.7	0.3-2.1
		0 Artificial Redds		5 Artificial Redds		5 Artificial Redds	
-6	64			0.0	-	0.0	-
-5	32			3.3	0-11	4.7	1-12
-3	8			26.2	21-30	33.2	23-46
-1	2			25.9	21-33	21.6	20-24
1	0.5	-		22.1	17-25	14.2	11-16
2	0.25			18.9	12-27	21.0	10-30
3	0.125			2.7	2-3	3.8	2-6
4	0.063			0.5	0.4-0.8	0.8	0.5-1.1
5	Silt-Clay			0.5	0.3-0.7	0.7	0.5-0.9

0.7%. Organic content of this fraction, analyzed in 1975 only, averaged 6% (range 3.6-10.9%). Some redds were coarse with 55% of the weight made up of gravels (32-8 mm), while others were sandy with 58% medium sand (0.5-0.25 mm). Sand (particles <2 mm) content averaged 40% in natural redds (range 12-83%) and 42% in artificial redds.

Brook trout spawning substrate in my study streams was finer than in Wyoming streams studied by Reiser and Wesche (1977) or in Lawrence Creek, Wisconsin, studied by Hausle and Coble (1976). Reiser and Wesche (1977) presented data for brook trout tailspills from which I calculated a GM particle size of 11.2 mm (coarse gravel) and about 13% sand (particles <2 mm) content. Hausle and Coble (1976) reported 10 natural redds had an average sand content of 31% and a range of 21 to 54% sand.

In addition to brook trout redds, I found one site in Benner Run that was judged a brown trout redd because of its coarse gravel, location at the lip of a pool, and the presence of more than 200 rose colored eggs. About 86% of the substrate was coarser than 6 mm and its GM particle size was 21.6 mm, which was much larger than the coarsest brook trout redd which had GM size of 14.2 mm. My observation was consistent with results of other studies. Reiser and Wesche (1977) found 70% of the substrate in brown trout tailspills from six Wyoming streams fell between 6.4 and 77.9 mm. In New Zealand, Hobbs (1937) analyzed seven brown trout redds and 75% of the substrate exceeded 6.4 mm diameter.

The substrate in many brook trout redds in Benner and Smays Runs was probably fine enough to reduce embryo survival and emergence. Hausle and Coble (1976) concluded that more than about 20% sand (particles <2 mm) in redds significantly reduced emergence. I calculated that 20% sand would be a GM particle size of approximately 7.5 mm (-2.90ϕ). Geometric mean particle size of spawning gravel has been related to embryo survival of salmon and trout and to gravel porosity and permeability, and provides a more complete description of substrate than "percent fines" (Platts et al. 1979; Shirazi and Seim 1979). Shirazi and Seim (1979) presented an emperical relationship of embryo survival to GM particle size of substrate within redds that indicated about 80% survival at a GM particle size of 15 mm, 50% survival at 11 mm, and 5% survival at 3 mm.

Permeability of Redds

Permeability (K) of 13 natural redds from Benner Run 1975-1976 averaged 0.802 cm/min with a range of 2.241 to 0.177 cm/min (Table 6). Permeability was measured only in 1975 and redd #14 was omitted from the average because much fine sand washed from the core and permeability kept increasing. No relationship was evident between permeability and GM particle size of redd substrate. Except for two outlying points, permeability remained relatively constant over the range of particle sizes. Initial permeability was highest, and it declined afterwards, probably due to sorting and compaction of the core.

The fine substrate of study redds may account for the relatively low permeability compared to those of other studies which have shown an inverse relation between permeability and percent fines and small gravel size (McNeil and Ahnell 1964; Cooper 1965) or GM particle size (Platts et al. 1979). McNeil and Ahnell (1964) found permeability of 19 samples from Alaskan pink salmon (Oncorhynchus gorbuscha) spawning areas ranged from 30 to 500 cm/min. Permeability was high when less than 5% of the substrate volume was fines but decreased when fines exceeded 15%. Mark VI standpipes (Terhune 1958) have been used by most other investigators to measure permeability of redds in situ. However, permeability measured

Table 6.—Permeability of substrate samples from wild trout redds of Benner Run 1975-1976. Coefficients of permeability (K) were measured in a constant head permeameter with a cross-section area of 78.6 cm^2. All readings were corrected to water viscosity at 20 C. Water passed continuously through each sample for five days and measurements were made on the second, fourth, and fifth days.

Redd	Discharge ml/min	Hyd. Gradient	Water Temp. C	Perm (K) cm/min	Mean K cm/min
1	134	1.44	9.4	1.586	
	62	1.44	8.9	0.723	1.085
	80	1.42	8.9	0.946	
2	33	0.97	8.9	0.571	
	40	0.99	8.9	0.679	0.573
	28	1.01	9.2	0.469	
3	61	0.83	8.9	1.234	
	31	0.82	8.9	0.635	0.767
	21	0.82	9.2	0.433	
4	53	1.22	9.4	0.741	
	38	1.23	8.9	0.519	0.497
	17	1.24	8.9	0.230	
5	52	0.84	8.9	1.040	
	39	0.84	8.9	0.780	0.781
	26	0.84	9.2	0.524	
6	40	0.44	9.4	1.550	
	12	0.44	8.9	0.458	0.803
	11	0.46	8.9	0.402	

7	121	0.52	9.4	3.972	1.994
	19	0.53	8.9	0.602	
	47	0.56	8.9	1.409	
8	85	1.06	9.4	1.367	0.766
	32	1.14	8.9	0.471	
	34	1.24	8.9	0.460	
9	79	0.91	8.9	1.458	0.962
	51	0.89	8.9	0.963	
	25	0.91	9.2	0.464	
10	24	0.52	9.4	0.787	0.362
	4	0.50	8.9	0.134	
	5	0.51	8.9	0.165	
11	21	1.18	8.9	0.299	0.177
	9	1.21	8.9	0.125	
	8	1.27	9.2	0.107	
12	151	0.78	9.4	3.251	2.241
	132	0.80	8.9	2.771	
	33	0.79	8.9	0.702	
13	44	1.89	9.4	0.391	0.277
	26	1.79	8.9	0.244	
	20	1.72	8.9	0.195	
14	1,002	3.42	9.4	4.925	8.661
	1,834	3.26	8.9	9.448	
	1,723	2.49	8.9	11.610	

with standpipes has shown great variability both spatially and temporally (Coble 1961; Moring 1975). Reiser and Wesche (1977) observed high permeabilities, 5.3 to 83 cm/min with a mean of 28.3 cm/min, in Wyoming brook trout redds. Their redds had coarse substrate; 70% of the substrate was between 3.4 and 50.5 mm in size with 13% sand.

Embryo Survival

Estimated survival to the eyed stage of wild brook trout embryos in natural redds averaged 69% (range 0 to 100%) and was greater than 60% in 17 of 27 redds excavated in winter (Table 7, Appendix E). (No traces of embryos or alevins were found in three redds.) These estimates reflect a correction for 18 and 20% decay and loss of dead embryos based on the disappearance of dead ova or embryos from sacks buried in the stream. Apparent survival averaged 73%, but because the ratio of eyed eggs and alevins to the total number of eggs and alevins found in each redd did not account for decay and disappearance of dead embryos, it tended to overestimate the true survival. I estimated about an 18% loss of ova in 1975 after 73 days in 2 to 9 C water temperature. In 1977, after 70 days in water temperatures of 4 to 8 C, about 20% of the dead embryos had disintegrated (Table 8). These are probably conservative estimates because the plastic mesh sacks held the dead embryos and fungus bound them to the mesh; consequently, it is reasonable to assume that fewer embryos were lost than would occur in natural redds. Hobbs (1937) found a 9% loss of dead brown trout embryos after 14 days in a perforated box, and McDonald (1960) observed a 22% loss of sockeye salmon (*Oncorhynchus nerka*) eggs in screened gravel boxes after approximately 223 days. Hausle and Coble (1976) buried dead brook trout embryos in perforated boxes; 98% of the embryos were intact after 53 days, 52% after 90 days,

Table 7.—Estimated survival to eyed stage of brook trout embryos in study redds. Redds were excavated in winter when embryos were about to hatch and redds containing no embryos or alevins are omitted.

Stream and Year	Redd	Eyed Embryos[a] and Alevins	Uneyed and Dead Embryos	Egg Pieces	Apparent Survival to Eyed Stage	Corrected Number of Dead Eggs	Corrected Survival in Natural Redds	Number Embryos Planted in Artificial Redds	Actual Survival in Artificial Redds
Natural Redds									
Benner Run 1975-1976	1	2	1	1	67	2	50		
	2	24	1	2	96	2	92		
	3	23	2	1	92	2	92		
	4	46	1	1	98	2	96		
	5	12	0	0	100	0	100		
	6	19	3	3	86	6	76		
	7	46	0	3	100	2	96		
	10	20	2	1	91	2	91		
	11	61	0	4	100	2	97		
	12	10	1	0	91	1	91		
	13	9	1	0	90	1	90		
	14	6	5	0	55	6	50		
Benner Run 1977-1978	1	31	2	0	94	3	91		
	3	1	0	0	100	0	100		
	5	22	24	0	48	30	42		

Smays Run 1977-1978	1	33	18	6	65	26	56		
	3	19	64	3	23	83	19		
	5	10	1	0	91	1	91		
	6	3	3	0	50	4	43		
	7	70	8	2	90	11	86		
	8	31	28	7	52	40	44		
	9	0	3	1	0	5	0		
	10	67	107	9	38	140	32		
	11	53	21	10	72	33	62		
	13	32	6	2	84	9	78		
	14	98	4	1	96	6	94		
	15	0	2	1	0	4	0		
Sum	-	748	308	58		423			
Mean					73		69		
Artificial Redds									
Benner Run 1977-1978	A	45	30	6	60			100	45
	B	21	52	2	29			100	21
	C	19	71	5	21			100	19
	D	23	48	14	32			100	23
	E	12	55	3	18			100	12
Smays Run 1977-1978	A	0	8	7	0			100	0
	B	1	16	12	6			99	1
	C	6	12	8	33			100	6
	D	22	26	12	46			107	21
	E	0	2	4	0			98	0
Sum	-	149	320	73				997	
Mean					25				15

[a] Includes all eyed embryos whether dead or alive at time of excavation.

Table 8.—Disappearance of brook trout ova and dead embryos buried in Benner Run. In 1975 three mesh sacks each containing 50 unfertilized ova were excavated on each sampling date. In 1977 two mesh sacks each containing 50 dead embryos were excavated on each date.

Sampling Date	Days in Stream[a]	Whole Ova or Embryos	Percent Loss
1975			
8 Nov	15	149	1
23 Nov	30	147	2
7 Dec	44	147	2
14 Dec	51	137	9
1976			
1 Jan	69	134	11
1977			
13 Nov	20	98	2
27 Nov	34	86	14
11 Dec	48	87	13
20 Dec	57	69	31
27 Dec	64	75	25
1978			
14 Jan	82	58	42
4 Feb	103	70	30
19 Feb	118	86	14
4 Mar	131	77	23

[a]Sacks were buried on 24 October.

and only pieces remained after 133 days. Stream water temperature averaged 6 C.

Few embryos were found in natural redds, but the embryos were large. The diameter of wild brook trout eggs averaged 4.6 mm with a range of 4.0 to 5.5 mm for 19 sets of measurements. Similar egg diameters of 3.3 to 5.0 mm were reported by Ricker (1932), Vladykov (1956), and Wydoski and Cooper (1966). Several redds contained six or less embryos and the highest (corrected for loss of dead embryos) was 207. The average number of embryos per redd, based on the 27 redds excavated, was 43. The low number of embryos reflects the size of female brook trout in these small infertile streams where 9-cm females averaged only 18 eggs and 19.5-cm females 213 eggs (Wydoski and Cooper 1966).

Survival of hatchery brook trout embryos in artificial redds averaged only 15%. Low egg viability and handling mortality probably accounted for the lower survival. While planting hatchery eggs, I noticed many with damaged yolk membranes, an indication of mechanical shock. Consequently, survival of hatchery embryos cannot be regarded as representative of survival of wild embryos in natural redds. Eggs used were from the late spawning 2 x 22 strain of brook trout from the Benner Spring Fish Research Station. I later learned that the egg viability of this strain was about 35% in 1977 because the brood fish had to be held in a drainage race where high temperatures and waste loads stressed the fish (W. Kennedy personal communication[4] and unpublished hatchery records). In other years, egg viability of this strain was about 77% with marked variability among eggs taken from individual fish.

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[4]W. Kennedy, Hatchery Superintendent, Benner Spring Fish Research Station, Bellefonte, PA.

Survival in natural redds was also estimated from the ratio of total number of eyed embryos and alevins recovered at excavation to the estimated total number of eggs deposited in redds by spawners. This method is not biased by disappearance of dead embryos and alevins (McNeil 1964). Survival estimated in this manner averaged 39%, lower than the 69% survival estimated from the ratio of eyed embryos and alevins to the total number (corrected for decay and loss of dead eggs) found at excavation. The reason(s) for the discrepancy was not apparent. However, the estimate of 39% was thought to be less accurate because of the variation inherent in the estimation of the number of eggs deposited per redd. Based on the potential number of mature females spawning and their egg production (Table 3), an average of 51, 52, and 100 eggs were deposited in each redd in Benner Run 1975, 1977, and Smays Run 1977, respectively. I calculated that the 12 redds in Benner Run 1975 had a total of 612 eggs, and 278 eyed embryos and alevins were recovered for a survival of 45%. I estimated 156 eggs were deposited in 3 redds in Benner Run 1977, but only 54, or 35%, reached the eyed stage. Embryo survival appears to have been higher in 1975 than in 1977. The higher survival in 1975 agrees with 1978 fish population estimates which also suggest the 1976 cohort (from eggs laid in 1975) was a strong one. Similarly, Smays Run had an estimated 1,200 eggs deposited in 12 redds, and 416 eyed embryos and alevins were excavated for a survival of 35%.

Estimated survivals of 39% or 69% in my study streams are generally lower than the 66 to 92% range of means reported by other investigators (White 1930; Hazzard 1932; McFadden 1961; Miller 1970; Hausle and Coble 1976) but fall within the 27 to 97% extremes observed by these authors. In addition, 0 to 29% survival has been reported in rigorous or stressed environments, such as high altitudes and low temperatures (White 1965) and sandy redds (Miller 1970). Perhaps conditions in the study redds lie between these.

Relation of Survival to Dissolved Oxygen in Substrate

Survival of wild brook trout embryos in natural redds was related ($r = 0.516$; $df = 25$; $p<0.01$) to mean dissolved oxygen concentration (Fig. 11) and followed the usual relationship of increased survival with increased intragravel dissolved oxygen (Wickett 1954; Coble 1961; McNeil 1966a; Moring 1975). Survival in artificial redds also was directly related ($r = 0.607$; $df = 8$; $p<0.05$) to dissolved oxygen concentration (Fig. 11).

Survival and mean dissolved oxygen were negatively related ($r = -0.582$; $df = 24$; $p<0.01$; and $r = -0.417$; $df = 24$; $p<0.05$; respectively) to geometric mean (GM) particle size of substrate in natural redds (Fig. 12). These inverse relationships were unexpected, particularly the inverse relationship between dissolved oxygen and substrate size. Although the redds consisted of a high percentage of fine material, they may have been shallow enough to permit sufficient interchange of well oxygenated surface water to produce good egg survival. These redds were not, however, so shallow as to eliminate a general relation between survival and intragravel dissolved oxygen concentration. The higher survivals (greater than 70%) were usually found in redds with GM particle size of substrate between 1 and 6 mm containing 25 to 56% sand (particles <2 mm). Incidental observations by others have indicated low survival of brook trout eggs in sandy redds (Brasch 1949; McFadden 1961; Webster 1962; Miller 1970). Shirazi and Seim (1979) assembled much of the

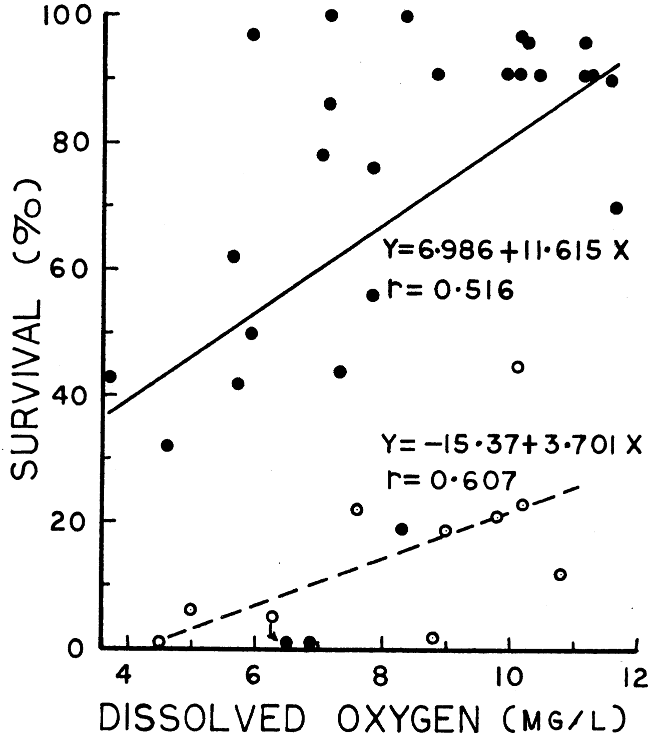

Figure 11. —Survival of brook trout embryos to the eyed stage in relation to mean dissolved oxygen concentration in natural (●——●) and artificial (O---O) redds. Lines placed by least squares method.

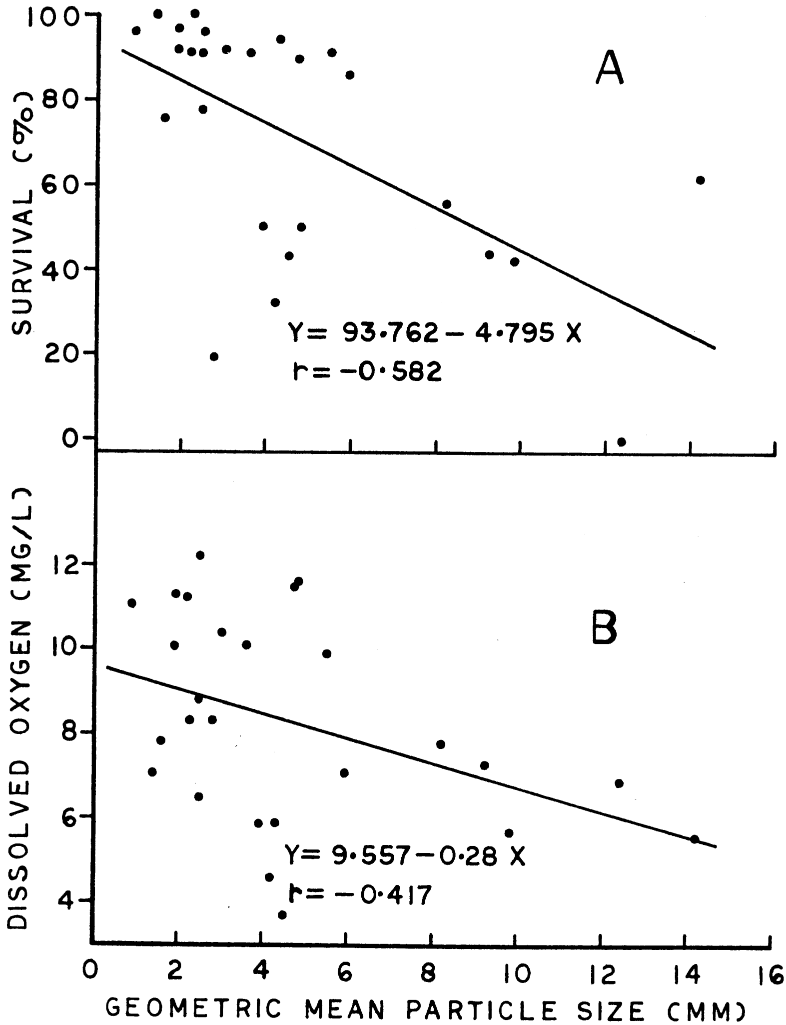

Figure 12. —Survival of brook trout embryos to eyed stage (A) and mean dissolved oxygen concentration (B) in relation to geometric mean (GM) particle size of substrate in natural redds. Lines were placed by method of least squares.

published and unpublished field and laboratory data on the relationship of coho salmon, sockeye salmon, steelhead trout (Salmo gairdneri), and cutthroat trout (Salmo clarki) survival to substrate particle size in spawning gravels. They found a direct curvelinear relation between GM particle size and survival. However, the substrate particle sizes usually exceeded 4 mm and therefore were generally coarser than those found in brook trout redds in the present study. Conversely, my data for brook trout and some for rainbow trout (Salmo gairdneri) are at odds with most other field and laboratory studies which have found direct linear or curvelinear relations between survival and particle size in trout and salmon redds. Hatch (1975) sampled 45 rainbow trout redds from three New York streams and found egg survival was not related to sand or silt and clay content of redds; however, sand content was never greater than 20%. Slaney (Parkinson and Slaney 1975, cited by Iwamoto et al. 1978) found a negative relation ($r = -0.78$) between survival to emergence and percent medium sand (~0.297 mm diameter) in rainbow trout spawning beds.

Emergence

Fry trap experiments failed to produce useful estimates of emergence success under natural conditions (Table 9, Appendix E). In two of the natural redds, no fry were trapped and no eggs or fry were found during excavation. In another redd, only one dead embryo was found. Emergence from these redds was considered zero as no fry were trapped. In the three remaining natural redds, only one fry was trapped. Excavation produced three live fry, three live embryos, plus a few dead embryos and fry.

A total of 128 fry emerged and were trapped from the four artificial redds containing 318 eyed eggs (Table 9). Emergence success among redds varied from 5 to 92% with a mean of 34%. There was no apparent relation

Table 9.—Numbers, length, and weight of live fry recovered in fry traps placed over natural and artificial brook trout redds and the content of the redds on excavation. Redds in which no evidence of embryos or fry were found are omitted from table.

	Redd	Date	Number Trapped	Mean Length (mm)	Mean Weight (g)	Total Trapped	Total Planted	Redd Contents Excavated 28 Apr 1978	Percent Emergence
Benner Run 1978	B	18 Mar 1978	2	21	.060				
		8 Apr 1978	2	22	.062	4	86 (15 wild)	3 dead fry 15 dead embryos	5
	4					0		1 live fry 3 dead fry 4 live embryos 9 dead embryos	0
		18 Mar 1978	2	20	.052				
		2 Apr 1978	3	24	.071	5	53 (41 wild)	3 dead embryos	9
	6					0	?	1 dead embryo	0

<u>Smays Run 1978</u>	2	5 Mar 1978	1	21	.061	1	?	20 dead embryos	5
	4					0	?	1 live fry 2 dead fry 30 dead embryos	0
	C*	5 Feb 1978	1	19	.056				
		20 Feb 1978	1	23	.078				
		5 Mar 1978	3	24	.074				
		19 Mar 1978	5	24	.069				
		1 Apr 1978	10	25	.066	20	72 (all wild)	3 dead embryos	28
	D*	5 Feb 1978	8	20	.058				
		20 Feb 1978	5	22	.068				
		5 Mar 1978	6	22	.060				
		19 Mar 1978	13	23	.064				
		1 Apr 1978	65	24	.079				
		15 Apr 1978	1	25	.082	98	107 (all wild)	3 eyed embryos 13 dead embryos	92

*Traps vandalized sometime between 15 Apr and 28 Apr 1978.

between emergence and substrate or dissolved oxygen. Brasch (1949) reported 79% emergence from 16 natural redds in a Wisconsin spring pond, and individual redds ranged between 20 and 90%. Hausle and Coble (1976) estimated 59% emergence from 10 natural redds in Lawrence Creek, Wisconsin. However, Miller (1970) calculated only about 1% emergence in a section of Lawrence Creek based on estimated egg deposition and early spring population estimates of emergent fry. My observations of emergence success are more in line with estimates of Miller (1970) and those for Pacific salmon (*Oncorhynchus* sp.). Moring and Lantz (1975) observed an average of 34, 24, and 30% emergence of coho salmon from three Oregon streams monitored over eight years. In individual redds, survival from deposition to emergence varied from 0 to 83%. McNeil (1966) excavated spawning areas of pink and chum salmon and estimated survival from spawning to emergence of 1 to 25%.

The rapid decay of dead alevins prevented adjustment of emergence estimates for loss of dead alevins. From 10 redds, only seven dead alevins were found in the gravel, suggesting few, if any, dead alevins would persist long enough to be present at excavation. Experiments in which dead alevins were buried in mesh sacks confirmed the fast rate of decay and disappearance; 100% were lost after about 100 days (Table 10). Redds were excavated in late April, more than 120 days after eyed eggs were planted in the artificial redds, and eggs in natural redds should have begun to hatch (estimated by developmental temperature units). Hobbs (1937) found 52% of the dead brown trout alevins in artificial redds "decomposed to an irrecoverable stage" in six to sixteen days at a water temperature of 9.9 C. McNeil et al. (1964) also noted disappearance of dead pink salmon alevins from spawning beds in 4.5 months.

Table 10. —Disappearance of dead brook trout alevins from mesh sacks buried in Benner Run. Each sack contained 50 alevins and two sacks were retrieved on each date.

Sample Date	Days in Stream	Whole Fry	Decayed Fry	% Loss
Buried 30 December 1977				
14 January 1978	15	22	30	48
4 February 1978	36	16	19	65
19 February 1978	51	20	6	74
4 March 1978	64	9	20	71
18 March 1978[a]	78	8	0	92
Buried 14 January 1978				
18 March 1978[a]	63	11	0	89
2 April 1978	78	5	2	93
15 April 1978	91	4	0	96
30 April 1978[b]	106	0	7	98

[a]Only 1 sack of 50 alevins.

[b]Eight sacks of 50 alevins each, total 400 alevins.

Brook trout fry began emerging in February, but peak emergence was in March and early April. Emergent fry were about 22.5 mm in total length and weighed 0.067 g (unweighted grand average). These figures are from both wild fry from natural redds and artificial redds containing at least 75% wild eggs. Miller (1970) reported mean length of emergent fry taken 15 March in Lawrence Creek to be 24.3 mm.

During periods of high flow, sand was deposited beneath the fry traps, and it may have influenced emergence. On occasion, two traps were completely filled with sand. When hoods were removed from some redds, a uniform circular layer of sand was found atop the redd, contrasting sharply with the surrounding stream bed. The effect of sand deposition on emergence could not be determined. Other studies have noted similar deposition of sand (Hausle and Coble 1976) and silt (Phillips and Koski 1969) beneath fry traps. Sand in redds can slow or reduce emergence of fry (Bjornn 1969; Hall and Lantz 1969; Hausle and Coble 1976; Phillips et al. 1975).

My observations of artificial redds in natural stream conditions are far from definitive, but the 34% emergence success seems reasonable considering the sandy substrate. Hausle and Coble (1976) found 25% sand in redds reduced emergence of brook trout alevins to 82%. They projected a 70% emergence of brook trout in Lawrence Creek. If their relation between emergence and percent sand in redds held for my artificial redds with an average of 48% sand, emergence should have been about 40%. Bjornn (1969) reported less than 10% emergence of chinook salmon (*Oncorhynchus tshawytscha*) in 40% sand (particles <6.4 mm), whereas steelhead trout emergence was 10% in 55% sand. Similarly, Phillips et al. (1975) found 8% coho salmon and 18% steelhead emergence in 70% sand (particles 1 to 3 mm).

If the problem of sand deposition under fry traps can be circumvented, the fry trap method offers the advantage of estimating actual emergence without the bias of decay and loss of dead embryos and alevins in redds. Also, emergence success accounts for effects of gravel composition and dissolved oxygen throughout the incubation period, thus giving a better estimate of actual numbers of fry recruited to the population. Disadvantages are that neither the number of eggs deposited nor the timing of mortality in redds are known.

Assuming my estimates of 69% embryo survival and 34% emergence are representative of the study streams, survival from egg deposition to emergence was only 23%. Survival appears much lower than generally reported for brook trout and is closer to values reported for salmon. Hausle and Coble (1976) estimated brook trout survival from egg deposition to emergence to be 59%. Brasch (1949) estimated 79% survival in Wisconsin spring ponds, and Webster (1962) observed 71% and 92% in two artificial spawning boxes. My estimate of 23% is in better agreement with Miller's (1970) 1% estimate for brook trout in Lawrence Creek and the 20 to 35% survival normally associated with Pacific salmon (Wickett 1962; McNeil 1966b; Moring and Lantz 1975).

Natural reproduction appeared to be more than adequate to perpetuate the wild brook trout populations in the study streams. Despite the estimated 23% survival in redds, density of fall fingerling and adult brook trout was high. About 1,600 YOY/hectare survived to October and density of older trout was 4,000/hectare. It is possible, however, that even slight siltation could clog the fine sand and gravel substrate of redds and cause a drastic decrease in survival of embryos and alevins. Increased road building, coal mining, oil and gas exploration and extraction, and timbering have silted many streams on the Allegheny Plateau and stringent sedimentation and erosion controls should be enforced. Wild brook trout streams may need strict safeguards to insure that sediment does not enter the stream.

SUMMARY

Brook Trout Populations

Benner Run standing stock estimates for October 1975 and 1978 averaged 58 kg/hectare and 6,067 trout/hectare. An estimated average of 53,046 eggs/hectare were deposited and 1,518 YOY were present in October. In October 1978, Smays Run had an estimated 60 kg/hectare and 4,507 trout/hectare of which 1,743/hectare were YOY, and 53,463 eggs/hectare were deposited. The diameter of wild brook trout eggs averaged 4.6 mm.

Site Selection

Wild brook trout in the study streams built small inconspicuous redds about 5-10 cm deep. Redds were often located immediately upstream of transitions in stream bed profile, such as at the lip of a small pool or upstream of a buried log. Egg pockets were sometimes in a gap between two large buried stones.

Temperature and Dissolved Oxygen in Redds

Intragravel water temperature in redds was almost identical to stream surface water temperature, and there was no indication of ground-water warming redds. Temperatures in redds exceeded 12 C only once and rarely rose above 9 C during the period of study. Dissolved oxygen concentration of intragravel water was about 2 to 3 mg/liter lower than surface water but tended to follow surface water concentrations. Dissolved oxygen in most redds averaged more than 6 mg/liter. In Benner

Run, means of individual redds ranged from 5.9 to 11.6 mg/liter in 1975 and 5.7 to 10.5 mg/liter in 1977-1978. Redds in Smays Run had means ranging from 3.7 to 9.9 mg/liter. Intragravel dissolved oxygen was highly variable, both spatially and temporally.

Substrate of Redds

Geometric mean (GM) particle size of redd substrate ranged from 0.6 mm (coarse sand) to 14.2 mm (gravel) diameter, and the grand average (mean of means) GM particle size of substrate samples was 3.3 mm. Redds contained less than 3% silt and clay and no cobbles (<64 mm diameter). Substrate of most redds was between 0.25 and 8 mm diameter. Average sand (particles <2 mm) content of redds was 48%. Cumulative size frequency distributions of redd substrates were similar for streams and between years. Permeability of 13 redds averaged 0.802 cm/min and was not related to GM particle size.

Embryo Survival

Based on the number of embryos and alevins versus the total number of embryos (corrected for decay and loss of dead embryos) found, estimated survival to the eyed stage averaged 69% but was highly variable; estimated survival of individual redds ranged from 0 to 100%. Survival to the eyed stage estimated from the ratio of the number of eyed eggs and alevins recovered to the estimated total number of eggs deposited in redds was 39%. However, the estimate of 39% seemed less reliable because of the variation inherent in the estimation of the number of eggs deposited in redds. Survival was directly related to mean dissolved oxygen concentration in redds but inversely related to GM particle size of redd substrate.

Emergence Success

Natural undisturbed redds over which fry traps were placed contained few or no embryos, or substrate limited emergence, for no fry were trapped. In five artificial redds planted with eyed eggs, emergence averaged 34% with a range of 5 to 92% and was not related to dissolved oxygen concentration or substrate composition. These fry began emerging in February, and peak emergence was in March and early April. Emergent fry were about 22.5 cm long and weighed 0.067 g.

Survival from Egg Deposition to Emergence and to Fall Fingerling

Using the estimates of 69% survival from egg deposition to eyed egg stage and 34% emergence success, I estimated that survival of brook trout from egg deposition to emergence was 23%. Based on estimates of egg deposition and YOY density in fall, survival from egg deposition to fall fingerling was 3%. However, reproduction and recruitment were apparently adequate to sustain these brook trout populations at relatively high densities.

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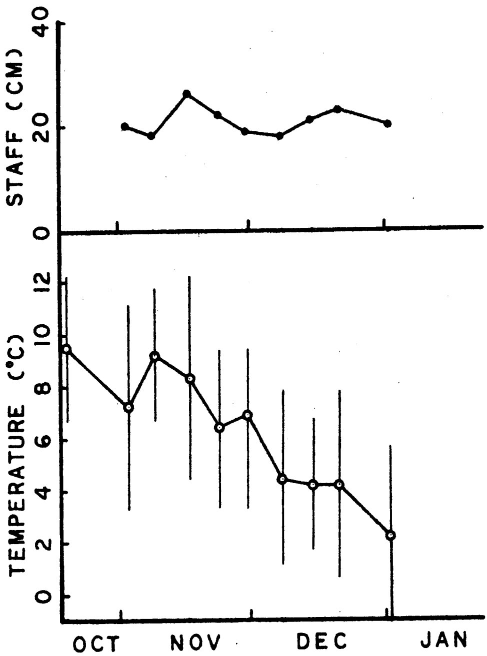
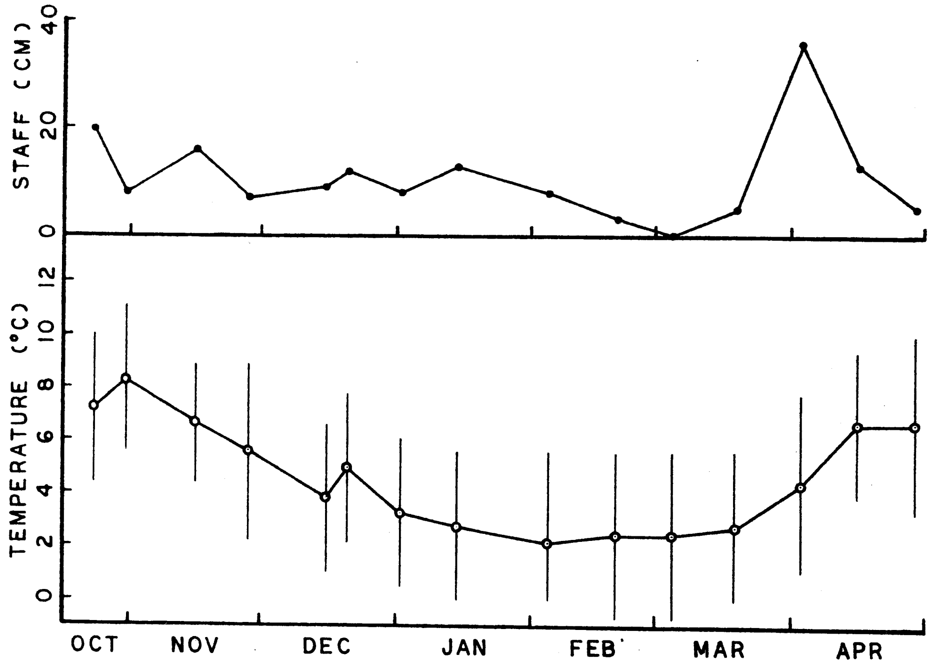
APPENDIX A

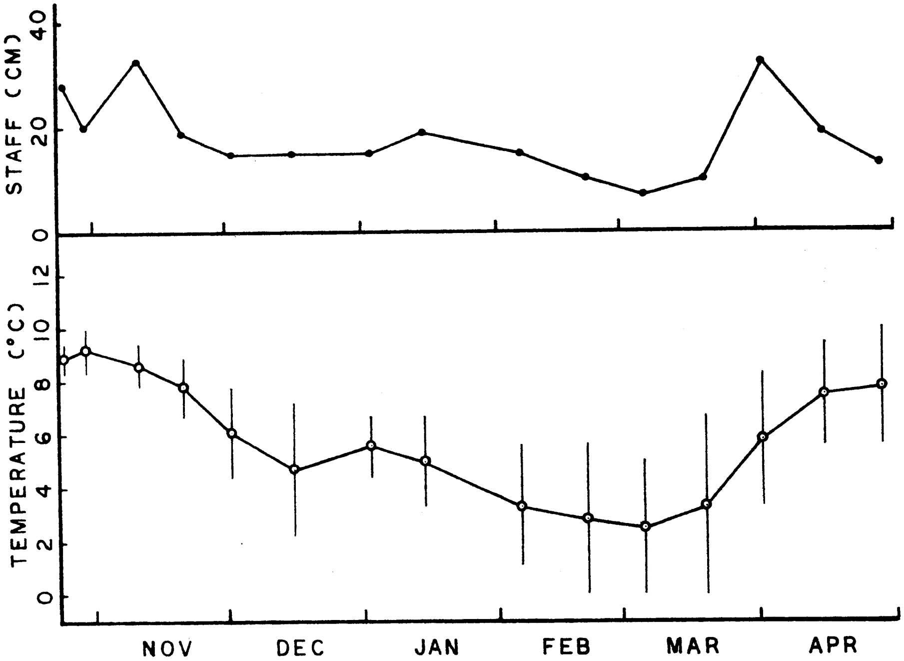
Staff gauge levels and stream water temperatures in Benner Run 1975-1976 and 1977-1978 and Smays Run 1977-1978



Appendix A.—Staff gauge levels and stream temperatures in Benner Run 1975-1976. Vertical bars denote temperature ranges and open circles denote midpoints of temperature ranges recorded by maximum-minimum thermometer.



Appendix A. —Staff gauge levels and surface water temperatures of Benner Run, 1977-1978. Vertical bars denote temperature ranges and open circles denote midpoints of temperature ranges recorded by maximum-minimum thermometer.

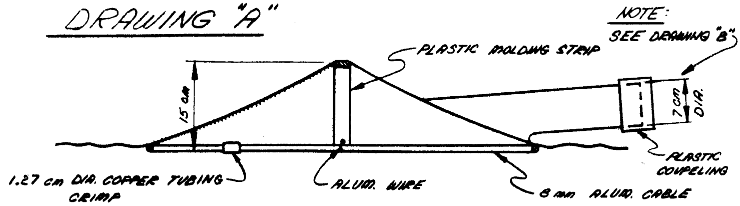


Appendix A.—Staff gauge levels and surface water temperatures of Smays Run, 1977-1978. Vertical bars denote temperature ranges and open circles denote midpoints of temperature ranges recorded by maximum-minimum thermometer.

APPENDIX B

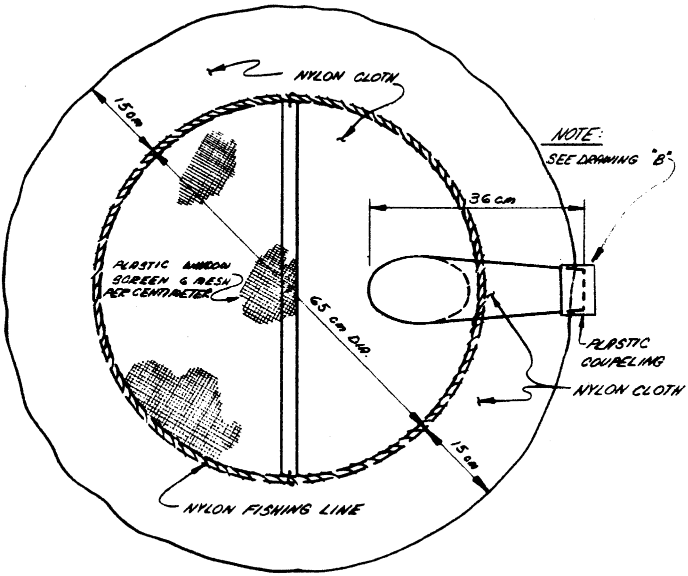
Design and construction details of fry traps used to capture brook trout fry emerging from redds

DRAWING "A"



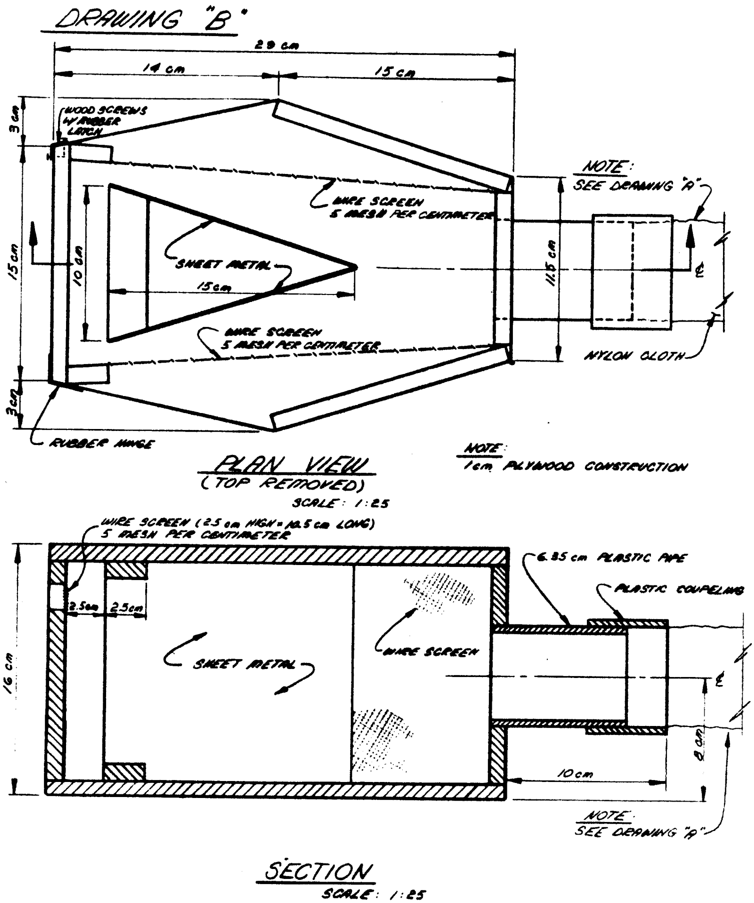
SECTION

SCALE: 1:75



PLAN

SCALE: 1:75


DRAWING "B"
29 cm
14 cm
15 cm
3 cm
WOOD SCREWS W/ RUBBER LATCH
WIRE SCREEN 5 MESH PER CENTIMETER
NOTE: SEE DRAWING "A"
15 cm
10 cm
SHEET METAL
15 cm
11.5 cm
WIRE SCREEN 5 MESH PER CENTIMETER
NYLON CLOTH
3 cm
RUBBER HINGE
PLAN VIEW (TOP REMOVED)
SCALE: 1:25
NOTE: 1 cm PLYWOOD CONSTRUCTION
WIRE SCREEN (2.5 cm HIGH × 10.5 cm LONG) 5 MESH PER CENTIMETER
6.35 cm PLASTIC PIPE
PLASTIC COUPELING
2.5 cm
2.5 cm
16 cm
SHEET METAL
WIRE SCREEN
10 cm
8 cm
NOTE: SEE DRAWING "A"
SECTION
SCALE: 1:25

APPENDIX C. —Intragravel dissolved oxygen in study redds.

	Redd	Dissolved Oxygen Mean (mg/liter)	Range	SD	n
	BENNER RUN 1975-76				
	Natural				
	1	5.9	4.2- 7.6	1.1077	8
U	2	10.4	8.2-11.3	1.107	8
P	3	11.3	10.0-12.2	0.8822	8
S	4	10.2	8.8-11.3	0.8551	8
T	5	8.3	6.2-10.4	1.3212	7
R	6	7.8	7.0- 9.0	0.6643	8
E	7	11.1	9.6-11.9	0.7387	8
A	8	7.7	4.8- 8.4	1.2235	8
M	9	11.5	10.2-13.3	1.0042	8
	10	10.1	6.0-11.9	1.8784	8
↓	11	10.1	8.2-11.3	1.1901	8
	12	11.2	10.1-11.7	0.5438	7
	13	11.5	10.2-12.3	0.7086	8
	14	11.6	10.3-13.2	0.9607	8
	Stream - Down	12.1	10.6-13.0	0.7791	8
	- Up	11.8	10.5-13.1	0.8194	8

BENNER RUN 1977-78

UPSTREAM ↓

Natural				
1	8.8	5.4-10.2	1.6643	10
2	9.7	7.1-10.6	1.1958	10
3	7.1	3.9- 8.3	1.5286	10
4 (Trapped)	8.9	5.5-11.2	1.355	17
5	5.7	3.0- 9.0	1.9223	12
6 (Trapped)	10.5	7.1-11.8	1.1271	16
7	5.6	1.6- 9.4	2.8146	15
Artificial				
A	10.1	9.5-10.8	0.6658	3
B (Trapped)	9.6	8.0-11.3	1.0878	11
C	9.0	8.5- 9.9	0.7572	3
D (Trapped)	9.2	5.1-10.8	1.6327	11
E	10.8	10.3-11.5	0.6429	3
Stream - Down	10.9	9.0-12.4	0.9674	13

APPENDIX C. —Continued

	Redd		Dissolved Oxygen			
			Mean (mg/liter)	Range	SD	n
			SMAYS RUN 1977-78			
	Natural					
	1		7.8	3.1- 9.9	1.8812	12
	2	(Trapped)	6.8	4.3- 9.1	1.4222	18
U	3		8.3	7.1- 8.8	0.4889	12
P	4	(Trapped)	8.4	6.0-10.7	1.0993	18
S	5		9.9	7.8-10.9	0.7605	12
T	6		3.7	0.6- 6.1	1.5251	11
R	7		7.1	2.5-10.4	2.2841	12
E	8		7.3	1.8- 9.4	2.1559	11
A	9		6.9	3.4- 9.8	1.9743	12
M	10		4.6	1.6- 8.4	2.5139	12
	11		5.6	2.0- 8.1	2.1754	12
↓	12	(Trapped)	6.3	3.1-10.6	1.9327	20
	13		6.5	3.6- 9.4	1.9884	12

14	6.0	4.3- 7.7	0.866	12
15	6.5	2.9- 9.8	2.7869	10
<u>Artificial</u>				
A	4.5	2.9- 5.9	1.5177	3
B	8.8	7.3- 9.9	1.3614	3
C (Trapped)	3.2	1.3- 7.1	2.1844	12
D (Trapped)	6.9	2.7-10.1	2.4861	12
E	6.5	2.4-10.3	3.9585	3
Stream - Down	10.4	9.7-11.2	0.4297	14
- Up	10.3	8.0-12.2	1.496	5

APPENDIX D. —Substrate particle size composition of study redds determined from cumulative frequency curves. Phi (Ø) sizes at 16, 50 and 84% were read from curves plotted for each redd. Mean phi values were calculated by the formula mean (Ø) = 16 Ø + 50 Ø + 84 Ø/3 where Ø = $-\log_2$ (particle size in mm) and the geometric mean calculated from the mean Ø value using the relation GM mean (mm) = $10^{(-1[0.301029 Ø])}$.

Type of Redd	Redd No.	Cumulative Percent Coarser Ø 16%	Ø 50%	Ø 84%	Mean Ø	Geometric Mean mm
			BENNER RUN 1975-76			
Natural	1	-4.2	-2.7	1.0	-1.97	3.9
	2	-3.9	-2.0	1.2	-1.57	3.0
	3	-3.1	-1.0	1.3	-0.93	1.9
	4	-3.4	-1.9	1.3	-1.33	2.5
	5	-3.4	-1.6	1.3	-1.23	2.3
	6	-3.0	-0.6	1.4	-0.73	1.6
	7	-1.7	0.5	1.6	0.13	0.9
	8	-5.0	-1.5	1.4	-1.70	3.2
	9	-3.0	-0.2	1.4	-0.60	1.5
	10	-4.0	-2.7	1.2	-1.83	3.6
	11	-3.2	-1.2	1.6	-0.93	1.9
	12	-3.2	-1.6	1.4	-1.13	2.2
	13	-4.8	-3.0	1.1	-2.23	4.7
	14	-4.9	-2.9	1.0	-2.27	4.8
	-	-	-	-	$\bar{X}$ -1.31 (2.5 mm)	-

BENNER RUN 1977-78

Natural	1	-3.3	-1.9	1.2	-1.33	2.5
	2	-5.1	-3.9	-0.7	-3.23	9.4
	3	-3.1	0.0	1.5	-0.53	1.4
	4	-2.8	-0.4	1.4	-0.60	1.5
	5	-5.1	-4.1	-0.7	-3.30	9.8
	6	-4.3	-3.3	-0.7	-2.77	6.8
	7	-1.0	1.2	1.8	0.67	0.6
	-	-	-	-	$\bar{X}$ -1.58 ø (3.0 mm)	-
Artificial	A	-3.2	-1.4	1.0	-1.20	2.3
	B	-3.6	-1.2	1.4	-1.13	2.2
	C	-3.9	-1.2	1.3	-1.27	2.4
	D	-3.1	-1.1	1.3	-0.97	2.0
	E	-4.5	-2.3	0.8	-2.00	4.0

APPENDIX D. —Continued

Type of Redd	Redd No.	Cumulative Percent Coarser Ø 16%	Cumulative Percent Coarser Ø 50%	Cumulative Percent Coarser Ø 84%	Mean Ø	Geometric Mean mm
			SMAYS RUN 1977-78			
Natural	1	-5.1	-3.7	-0.3	-3.03	8.2
	2	-4.2	-3.2	1.4	-2.00	4.0
	3	-3.4	-2.3	1.2	-1.50	2.8
	4	-3.1	1.1	1.9	-0.03	1.0
	5	-5.1	-3.4	1.1	-2.47	5.5
	6	-4.7	-3.1	1.3	-2.17	4.5
	7	-5.1	-3.6	1.0	-2.57	5.9
	8	-4.9	-3.6	-1.1	-3.20	9.2
	9	-5.1	-4.1	-1.7	-3.63	12.4
	10	-4.3	-2.7	0.8	-2.07	4.2
	11	-5.1	-4.3	-2.1	-3.83	14.2
	12	-3.0	1.2	1.9	0.03	1.0
	13	-3.9	-1.6	1.6	-1.30	2.5
	14	-4.4	-3.0	1.1	-2.10	4.3
	15	N/A - Eggs deposited in cracks of buried log				
	-	-	-	-	$\bar{X}$ -2.13 Ø (4.4 mm)	-
Artificial	A	-4.0	-1.9	1.3	-1.53	2.9
	B	-3.9	-1.5	1.4	-1.33	2.5
	C	-3.4	-0.5	1.6	-0.77	1.7
	D	-3.7	-1.7	1.4	-1.33	2.5
	E	-4.7	-3.3	0.3	-2.57	5.9

APPENDIX E.—Contents of natural and artificial brook trout redds excavated during the study.

Redd	Excavation Date	Embryos				Alevins			Remarks
		Live Eyed	Dead Eyed	Dead Uneyed	Pieces[a]	Live	Dead	Decayed	
					BENNER RUN 1975-1976				
Natural									
1	12/31/75	2	-	1	1	-	-	-	
2	12/31/75	24	-	1	2	-	-	-	
3	12/31/75	23	-	2	1	-	-	-	
4	12/31/75	-	-	1	1	46	-	-	
5	12/31/75	12	-	-	-	-	-	-	
6	12/31/75	6	-	3	3	6	4	3	
7	12/31/75	33	1	-	3	12	-	-	
8	1/ 2/76	0	0	0	0	0	0	0	False redd
9	1/ 2/76	0	0	0	0	0	0	0	False redd
10	1/ 2/76	19	-	2	1	1	-	-	
11	1/ 2/76	57	3	-	4	1	-	-	
12	1/ 2/76	3	-	3	-	7	-	-	
13	1/ 2/76	9	-	1	-	-	-	-	
14	1/ 2/76	5	1	5	-	-	-	-	

BENNER RUN 1977-1978

Natural									
1	12/20/77	31	-	2	-	-	-	-	
2	12/20/77	0	0	0	0	0	0	0	False redd
3	12/20/77	1	-	-	-	-	-	-	
4	4/27/78	2	2	7	5	1	-	3	Fry trap redd
5	12/20/77	15	6	24	-	1	-	-	
6	4/27/78	-	-	1	-	-	-	-	Fry trap redd (vandalized)
7	4/27/78	0	0	0	0	0	0	0	Fry trap redd (vandalized), false redd
Artificial									
A	12/27/77	39	6	30	6	-	-	-	
B	12/27/77	17	4	52	2	-	-	-	
C	12/27/77	13	6	71	5	-	-	-	100 hatchery eggs
D	12/20/77	21	2	48	14	-	-	-	planted in each artificial
E	12/20/77	10	2	55	3	-	-	-	redd 10/28/77
F	11/ 1/77	25	-	67	-	-	-	-	
G	11/ 5/77	45	-	49	-	-	-	-	
Artificial Redds Replanted and Excavated									
B	4/27/78	-	7	7	5	7	-	2	86 eyed eggs planted 12/27/77
D	4/27/78	-	2	-	2	5	-	-	53 eyed eggs planted 12/20/77
									Both redds fry trapped

APPENDIX E. —Continued

Redd	Excavation Date	Embryos				Alevins			Remarks
		Live Eyed	Dead Eyed	Dead Uneyed	Pieces[a]	Live	Dead	Decayed	
					SMAYS RUN 1977-1978				
Natural									
1	12/17/77	22	11	18	6	-	-	-	
2	4/28/78	1	-	7	2	1	-	-	Fry trap redd
3	12/17/77	19	-	64	3	-	-	-	46 dead eggs looked live but undeveloped
4	4/27/78	-	8	8	29	1	2	-	Fry trap redd
5	12/17/77	10	-	1	0	-	-	-	Yellow eggs looked live but undeveloped
6	12/17/77	1	2	3	0	-	-	-	
7	12/17/77	3	3	8	2	64	-	-	
8	12/17/77	18	6	28	7	7	-	-	
9	12/17/77	-	-	3	1	-	-	-	
10	12/18/77	49	18	107	9	-	-	-	
11	12/18/77	-	16	21	10	37	-	-	
12	4/28/78	0	0	0	0	0	0	0	Fry trap redd (vandalized), false redd

13	12/18/77	32	-	6	2	-	-	-		
14	12/18/77	96	2	4	1	-	-	-		
15	12/18/77	-	-	2	1	-	-	-		
<u>Artificial Redds</u>										
A	12/28/77	-	-	8	7	-	-	-	100}	
B	12/28/77	-	-	16	12	1	-	-	99}	
C	12/18/77	5	-	12	8	1	-	-	100}	Number of hatchery
D	12/18/77	16	6	26	12	-	-	-	107}	eggs planted
E	12/28/77	-	-	2	4	-	-	-	98}	10/28/77
F	11/ 5/77	23	-	71	-	-	-	-	100}	
G	11/ 5/77	-	-	97	-	-	-	-	100}	
<u>Artificial Redds Replanted and Excavated</u>										
C	4/28/78	-	-	-	5	20	-	-	72}	Number of eyed eggs planted
D	4/29/78	-	2	10	11	98	-	-	107}	12/18/77 Both redds fry trapped (vandals ripped out traps)

[a]One piece equals about one half an egg. Eggshells were not counted.

EMBRYO SURVIVAL, SUBSTRATE COMPOSITION, AND DISSOLVED OXYGEN IN REDDS OF WILD BROOK TROUT

by

Bruce A. Hollender

A Thesis
submitted in partial fulfillment of the
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