COMPARISON BETWEEN THE SUBSURFACE ENVIRONMENT OF BROWN TROUT (*Salmo trutta*) REDD AND NONREDD SITES IN TWO NORTH CAROLINA STREAMS

by

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ABSTRACT

The gravel environment of 30 brown trout (*Salmo trutta*) redds and adjacent nonredd sites in two western North Carolina streams were studied during the incubation period in 1979-1980 and 1980-1981. Intragravel water temperature, dissolved oxygen concentration, and percent oxygen saturation were highly correlated with surface water measurements, indicating that intragravel water is of surface origin. Permeability ranged from 250 to 149,350 cm/hr and averaged 6,150 cm/hr. Apparent velocity varied from 0 to 1,000 cm/hr and averaged 30 cm/hr. Permeability in redds was significantly greater than at nonredd sites. No significant differences in apparent velocity were found between redd and nonredd sites. No consistent differences in permeability or apparent velocity were found between streams or over time. Permeability and apparent velocity decreased significantly with depth.

Freeze cores were collected from redd and nonredd sites and divided into three 10-cm layers for analysis. Geometric mean diameter, sorting coefficient, fredle index, percent fines <2.00 mm, and percent porosity were highly variable and averaged 11.8 mm, 2.8, 4.2, 17.0 percent, and 19.0 percent, respectively. No significant differences were found among factors tested. Correlations between these gravel indices and permeability and apparent velocity were low. The gravel and intragravel environments appeared to be adequate for larval survival. Measurements did not reveal any clear trends during the incubation period. Brown trout did not by choice or redd construction appear to select or create (by redd construction) a subsurface environment different from the surrounding stream bed.

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INTRODUCTION

Fisheries biologists and land managers are often concerned with the maintenance of self-sustaining trout populations. During the time from egg deposition to alevin emergence, salmonids can experience high mortality from natural causes. This period of larval development may also be affected by various land management activities. Before the effect of these activities on intragravel survival of brown trout (*Salmo trutta*) can be determined, information on the subsurface environment of redds in undisturbed stream systems is needed.

Trout deposit their eggs in gravel substrates where the developing embryos and fry are protected from exposure to light, displacement, and predation. Subsurface water flow supplies dissolved oxygen and removes metabolic wastes. Suitability of the intragravel environment can be characterized by basic water quality parameters such as temperature, dissolved oxygen concentration, percent oxygen saturation, and two variables that describe intragravel water flow--permeability and apparent velocity. All of these parameters can affect the survival-to-emergence of salmonid fry (Iwamoto et al. 1978).

Water temperature influences the rate of growth, development, and metabolic processes of the salmonid embryo (Garside 1966). Lower and upper temperature limits for incubation range from 4.4 to 13.3^{o} C for most salmonids (Reiser and Bjornn 1979), although eggs can withstand extended periods at very low temperatures if they are acclimated slowly to the lower temperatures. Low water temperature can cause embryo mortality through the formation of anchor ice in the substrate (McNeil 1966, Cloern 1975, Reiser and Wesche 1977). Even in the southern Appalachians, low water temperatures have been related to increased larval fish mortality (Lennon 1967, LaRoche and Pardue 1980). Low water temperatures that prolong the development period subject the embryos and fry to increased mortality through redd washout, sedimentation, disease, or predation.

Dissolved oxygen concentration can affect the size, development, and survival rates of salmonid fry (Silver et al. 1963). The concentrations required for embryo survival and growth vary with developmental stage, with maximum dissolved oxygen levels being required during hatching (Wickett 1954). Hayes et al. (1951) found that the dissolved oxygen concentration required for hatching Atlantic salmon (Salmo salar) eggs (7.1 mg/l) was 150 percent greater than the concentration required for newly deposited eggs(2.8 mg/l). A wide range (0.72-10.00 mg/1) of critical values of dissolved oxygen has been reported for various salmonid species. Concentrations at or near saturation, with temporary reductions to no less than 5.0 mg/1, have been recommended by Reiser and Bjornn

(1979). Definition of a critical dissolved oxygen level is further complicated by the influence of intragravel water velocity (Shumway et al. 1964).

The primary source of intragravel dissolved oxygen is stream surface water (Vaux 1962). The interchange of oxygenated water from the stream surface into the stream bed is influenced by several hydrologic and physical features of stream water and substrate. Intragravel dissolved oxygen concentration has been correlated with stream gradient (Vaux 1962) and discharge (Wickett 1958, McNeil 1962). Intragravel dissolved oxygen levels are also influenced by gravel permeability and size composition (Woods 1980) and by the relative roughness of the stream-substrate interface (Cooper 1965). Increased sedimentation after logging can decrease the concentration of dissolved oxygen in redds of coho salmon (*Oncorhynchus kisutch*) and cutthroat trout (*Salmo clarki*) (Ringler and Hall 1975). Andrew and Geen (1960) found that dissolved oxygen concentrations in sockeye salmon (*O. nerka*) redds were significantly higher than in undisturbed sites and related these higher levels of dissolved oxygen to less fine sediment in the redds.

Permeability or percolation rate (K_{10}), a measure of the ease with which water can move through substrates, is determined by the gravel environment and local hydrologic features. The characteristics of the stream bed that affect permeability are the shape, packing, sorting, and size composition of substrate particles (Cooper 1965). The shape of sediment particles influences interstitial pore space; angular particles create irregular water passages, while spherical particles create more uniform pore spaces. Sediment packing can also influence substrate pore space. The degree of packing is a function of gravel shape, size composition, and compaction (Cooper 1965). The uniformity among substrate particles is a measure of the sorting of the sediments. Stream flow controls the sorting of streambed sediments by continual suspension and deposition of particles. The hydrologic parameters that can influence permeability include hydraulic gradient (the slope of the line created by the piezometric head over distance), water viscosity, and density. Hydraulic gradient is determined primarily by localized changes in streambed profile (Vaux 1962), whereas water viscosity and density are functions of water temperature.

Permeability has been correlated with survival of pink salmon (*O. gorbuscha*) and chum salmon (*O. keta*) (Wickett 1958) and brown trout larvae (Turnpenny and Williams 1980). In southeastern Alaska, McNeil and Anhell (1964) found high permeability when the amount of fine sediment (<0.833 mm) comprised less than 5 percent of stream gravels and low permeability when fine sediment exceeded 15 percent. Permeability has been found to decrease over the period of larval development, particularly in streams with high sediment loads (Wickett 1962, Wells and McNeil 1970); this decrease was ascribed to the infiltration of fine sediment into the spawning gravel. In streams with low sediment load, permeability did not decrease over time (Reiser and White 1981).

Apparent velocity (V)--the volume of water flowing per unit of time through a given area within the streambed--has been related to salmonid egg survival (Shelton 1955, Gangmark and Bakkala 1960, Phillips and Campbell 1961, Cooper 1965, Turnpenny and Williams 1980), size of emergent alevins (Shumway et al. 1964), and dissolved oxygen concentration (Wickett 1962, Cooper 1965). Decreases in apparent velocity have been related to increased levels of fine sediments (Peters 1962, Bianchi 1963).

Survival of salmonid larvae has been related to gravel composition by many investigators (McNeil and Anhell 1964, Cooper 1965, Bjornn 1969, Cederholm and Lestelle 1974, Phillips et al. 1975, Hausle and Coble 1976, Shirazi and Seim 1979). Several indices have been derived to characterize gravel composition. A commonly used parameter is percent fines, defined by a range of sizes (6.3 to .833 mm). Another parameter used to describe gravel composition is geometric mean diameter (dg), a statistical measure to describe the entire textural composition of the gravel (Inman 1952). Platts et al. (1979) found geometric mean diameter highly correlated with porosity and permeability. Shirazi and Seim (1979), using data from a wide variety of sources, related geometric mean diameter to percent survival of salmonid larvae. A third index often used is sorting coefficient (sc). It measures the variation in particle size distribution and has been inversely related to permeability (Lotspeich and Everest 1981) and void space (Ottaway et al. 1981). The fredle index (fi) estimates both the central tendency and variance of particle sizes within the substrate and has been related to pore size and relative permeability (Lotspeich and Everest 1981). Neilson and Banford (1983) found that the fredle index was correlated with relative productivity of chinook salmon (O. tshawytscha) spawning sites.

The suitability of a particular location for development of salmonid eggs and embryos appears to be a function of both gravel and intragravel characteristics. These characteristics are defined by stream flow, sediment load, and streambed configuration and gradient. In order to determine which factors may affect the survival of brown trout embryos in southern Appalachian trout streams, these characteristics were monitored during the period of larval development. Both redd and nonredd sites were studied over the incubation period to determine if (1) the fish select an environment different from the surrounding undisturbed stream bed or create a different environment by redd construction, and (2) changes occur in gravel and intragravel characteristics of these sites during this period.

MATERIALS AND METHODS

Study Area

A 750-m reach of the upper South Mills River (W 82°45'00", N 35°22'30"), a third-order stream, and a 750-m reach of one of its second-order tributaries, Poplar Creek, were chosen as study areas (Figure 1). These two streams in Transylvania County, North Carolina drain a forested watershed of 485 ha within the Pisgah National Forest. The overstory along these streams consisted of mixed oak (*Quercus* spp.) and hickory (*Carya* spp.) stands interspersed with eastern hemlock (*Tsuga canadensis*) and white pine (*Pinus strobus*). The riparian vegetation was predominantly rhododendron (*Rhododendron* spp.), laurel (*Kalmia latifolia*), and dog hobble (*Leucothoe* spp.). The elevation of both watercourses averaged 980 m with a mean gradient of 0.05 percent. South Mills River ranged from 3 to 10 m in width the study area, while Poplar Creek was 0.5 m wide in the upper reaches to 5.0 m at its confluence with the South Mills. The streambed consisted of isolated gravel pockets interspersed among larger boulders, with some exposed bedrock. Sediment input was from natural erosion of stream banks and overland flow. Both stream sections were chosen for study because they were accessible during the study period, had low gradients that resulted in long reaches of suitable substrate, and contained self-sustaining wild brown trout populations.

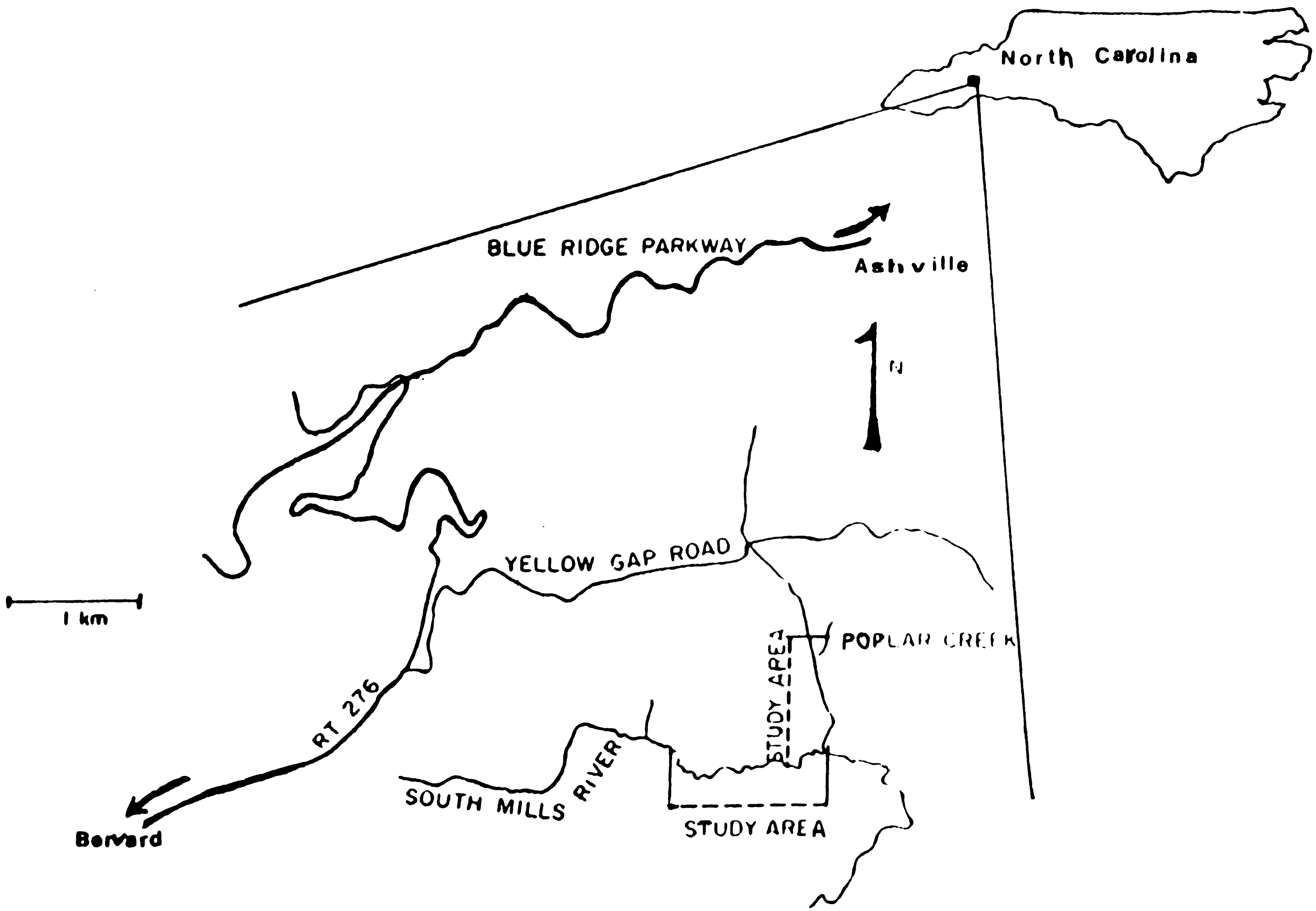

Figure 1: Poplar Creek and South Mills River study area, Transylvania Co. NC.

Beginning the second week of September in 1979 and 1980, study sections were surveyed at least three times per week to locate brown trout redds. Sample sites were located in both streams by direct observation of brown trout spawning activities and indirectly by finding recent streambed disturbance. When spawning pairs were observed over redds, lengths of fish were estimated. All redds were confirmed by carefully moving aside the top layer of gravel until eggs were seen; gravel was then replaced. Location of each redd was recorded by measuring the distance along a transect from the center of the redd to stakes driven into each stream bank. The search for redds continued until mid-November, after which spawning behavior was rarely observed. Fifteen redds were located in 1979, five on South Mills River and ten on Poplar Creek; thirty-two redds were found in 1980, twelve on South Mills and twenty on Poplar Creek. Six additional redds were located in 1981. Redds were generally indistinguishable from surrounding substrates after the first rain storm each year; the characteristic mound-depression area, and the "clean" gravel of the redds vanished following high water.

During both years, spawning activity was first observed in late September and continued through mid-November. Time that the eggs remained in the gravel was designated by weeks, beginning the third week in November (week 1). The study continued over a 25-week period ending the second week of May (Appendix 1). In both years, emergence began the first week of April (week 21) and continued through week 25.

At each site, the redd was paired with an adjacent nonredd location (within 50 cm) in an area of similar substrate composition and water flow. Sites were numbered and then randomly assigned to the proposed sampling schedule.

Intragravel Characteristics

Temperature (^{o}C), dissolved oxygen (mg/1), permeability (cm/hr), and apparent velocity (cm/hr) were measured using the Mark VI standpipe techniques(Pollard 1955, Terhune 1958, Wickett 1958). Water temperature and dissolved oxygen were measured in the standpipes and in the surface water surrounding the standpipes with a dissolved oxygen meter (Yellow Springs Instrument Co., Colorado Springs, CO). Surface water velocity (cm/sec) was measured upstream of each standpipe at two-thirds the water depth using a Gurley pygmy (W. and L. E. Gurley Co., Troy, NY) or a Marsh-McBirney (Marsh-McBirney Co., Gaitersburg, MD) current meter. Percent oxygen saturation was determined from dissolved oxygen concentration, water temperature, and elevation. Permeability was estimated by measuring the influx of water over time by lowering the water level to create a hydraulic head of known volume. Using a laboratory-generated calibration curve (Terhune 1958), this rate was converted into a measure of permeability. To compare permeability readings, measurements were standardized to 10^{o}C to correct for differences in water viscosity. Apparent velocity was estimated by injecting dye into a chamber created within the standpipe and measuring the rate of dilution. Using this rate of dye dilution and the permeability readings, estimates of apparent velocity were obtained from laboratory-generated calibration curves (Terhune 1958). Permeability and apparent velocity were both expressed in cm/hr. Due to the scale of the calibration curves, the reported permeability readings were rounded to the nearest 50 cm/hr and the apparent velocity readings to the nearest 10 cm/hr.

Intragravel and surface water temperatures were measured using 90-day recording thermographs (Ryan Instrument Co., Seattle, WA). An intragravel thermograph was buried in each stream to a depth of 20 cm, and an instream thermograph was suspended in the water column. Temperatures were recorded from 1 November through 30 April in 1979-80 and in 1980-81.

Gravel Characteristics

Substrate samples, 30 cm in depth, were collected by freeze coring (Walkotten 1976). Sampling time for each core was four minutes. Each core was divided into three 10-cm layers which were returned to the laboratory and kept frozen until processing. Each core layer was weighed while still frozen, then thawed and oven dried, reweighed, and sieved. Percent composition of sediment was determined using the following sieve sizes (mm): 50.8, 25.4, 19.0, 13.2, 6.32, 4.76, 3.36, 2.00, 0.841, 0.420, 0.212, 0.106, and less than 0.106 mm. The volume of material retained by each sieve was determined by weighing the volume of water displaced by that sample. Geometric mean diameter (dg), sorting coefficient (sc), and fredle index (fi) were calculated using the following equations (Lotspeich and Everest 1981):

(1) $dg = d_1^{w_1} \times d_2^{w_2} \times \ldots d_n^{w_n}$

where d = midpoint diameter of particles retained by a given sieve,

and

w = decimal fraction by volume of particles retained by a given sieve.

(2) $sc = \frac{d_{75}}{d_{25}}$

where d_{75}, d_{25} = diameter at which 75 or 25 percent of the particles, respectively, are smaller on a volume basis.

(3) $fi = \frac{dg}{sc}$

Estimates of porosity were calculated for each layer using the formula (Pollard 1955):

(4) $\text{Porosity (\%)} = \frac{\text{volume of water (ml)}}{\text{volume of water + sediment (ml)}}$

The volume of water within a sample was estimated as the loss of water of that sample frozen and oven dried. Fines were defined as sediment particles less than 2.00 mm in diameter (Platts et al. 1979), unless otherwise specified.

Egg Deposition

Number, depth, and distribution of eggs deposited within redds were determined by two methods: freeze coring and excavation. Before a redd was freeze-cored, a 1.5-m fine-mesh net (2 mm^2 mesh) was positioned 1 m downstream. After the core was extracted, an area of approximately 1 m^2 surrounding the core site was removed by hand to a depth of 25 cm. Dislodged eggs and fry drifting into the net were recovered, enumerated, and replanted. The depth and number of eggs visible in the freeze core were also recorded. Before each layer was analyzed in the laboratory, the thawed sample was checked for additional embryos or fry that had not been visible on the core surface.

The second method involved excavating randomly selected redds. First, the fine mesh seine was placed approximately one meter downstream to collect any eggs or fry lost during excavation; a modified Hess sampler was then placed on the upstream edge of the redd, worked into the gravel to a depth of approximately 10 cm, and the gravel within the sampler was removed manually. If eggs were seen, the depth from the streambed surface and the area within the

0.1-m^2 Hess sampler were recorded. Gravel was removed to a depth of 25 cm or until the substrate could no longer be dislodged easily. This process continued until no further eggs were collected. The net was then checked for dislodged eggs or fry. The areas within each Hess samples that contained eggs was totaled to generate an estimate of the area of egg deposition with the excavated redd. Eggs were counted and replanted using techniques described by Harshbarger and Porter(1979), and captured fry were counted and released. Due to the small number of redds located in 1979-1980, no redds were excavated. Five redds were excavated in 1980-1981 and six in 1981-1982. Estimates of egg loss were generated by re-excavating a previously planted redd, using the modified Hess sampler as described above and counting eggs and fry collected.

Data Collection and Analysis

Two separate sampling regimes were used to collect and analyze the standpipe and freeze core data over the study period:

1. <u>Weekly measures of redd and nonredd locations</u>--Intragravel characteristics at the depth of egg deposition (10 cm) were measured weekly during each of the two study periods at two randomly selected sites on Poplar Creek and at one randomly chosen site on South Mills River. The sites in 1979-1980 were naturally different from those selected in 1980-1981 because of the different redd locations. Each site consisted of a redd and

a nonredd location. Standpipes were driven 10 cm into the substrate at the redd and nonredd locations within each site. Intragravel water temperature, dissolved oxygen, permeability, and apparent velocity were measured weekly from each standpipe, beginning the third week of November and continuing for 25 weeks (Appendices 2-9). At the same time, surface water temperature, dissolved oxygen, and velocity were recorded. The weekly measurements were grouped into five time periods for data analysis: weeks 1-5=1, 6-10=2, 11-15=3, 16-20=4, and 21-25=5.

2. Depth profiles of redd and nonredd sites--Gravel and intragravel characteristics were measured three times during each of the two study periods at three depths (0-10, 11-20, and 21-30 cm) within the substrate at randomly chosen sites. In the 1979-1980 field season, the intragravel variables were sampled at two sites per sample date. In 1980-1981, due to equipment breakdown, the number of sites sampled per sample date was 1, 2, and 3, respectively (Appendices 10-17). Freeze cores were collected at three sites per sample date--where standpipe data were collected and from randomly chosen undisturbed sites (Appendices 18-27). Samples were collected during weeks 8, 17, and 21 in 1979-1980, and during weeks 4, 11, and 17 in 1980-1981. Since sampling was destructive, in this regimen new sites were sampled on each sample date. Each site again consisted of paired redd and nonredd locations. To measure the intragravel characteristics (the same parameters discussed above), standpipes were driven

into the substrate in 10-cm increments and allowed to stabilize for 24 hours at each increment before readings were taken.

Nonparametric statistical methods were used to test for significant differences in characteristics between redd and nonredd locations, between streams (Poplar Creek and South Mills River), over time, and among depths (Table 1). In order to test for significant differences in intragravel water temperature, dissolved oxygen concentration, and percent oxygen saturation among the independent variables (redd-nonredd, stream, time, and depth), the difference between surface and intragravel measurements of each parameter was used as the dependent variable in the analysis. When time was tested, each of the two study periods (1979-1980 and 1980-1981) was analyzed separately, with streams, redd- nonredd, and depth used as blocking factors. When depth was tested, the blocks used were year, week, redd-nonredd, and stream. In order to determine if the presence of standpipes had an impact on the gravel parameters, sites with standpipes were compared to undisturbed core sites using the Mann-Whitney U test. The association between the variables was measured using the Spearman rank order correlation (Hollander and Wolfe 1973). The significance level used for acceptance of null hypotheses was $p<.10$. Values of p less than .10 are specifically reported. The mean values of permeability and apparent velocity reported are backcalculated from natural log-transformed data.

Table 1. Listing of response variables and the nonparametric treatment analyses used to test them.[1]

TREATMENT	STATISTICAL TEST	RESPONSE VARIABLES
Redd vs nonredd	Wilcoxon Rank Sum Test[2]	Intragravel parameters
		Permeability
		Apparent velocity
		Stream water temperature-intragravel water temperature
		Stream dissolved oxygen concentration-intragravel dissolved oxygen concentration
		Stream percent oxygen saturation-intragravel percent oxygen saturation
		Gravel parameters
		Geometric mean diameter
		Sorting coefficient
		Fredle index
		Percent fines less than 2.00 mm
		Porosity
Poplar Creek vs South Mills River	Mann-Whitney U Test[2]	Intragravel parameters
		All
		Gravel parameters
		All
Standpipe vs No standpipe	Mann-Whitney U Test[2]	Gravel parameters
		All
Time	Friedman Rank Sum[3] Multiple Comparison Test	Intragravel parameters
		All
		Gravel parameters
		All
Substrate depth	Friedman Rank Sum[3] Multiple Comparison Test	Intragravel parameters
		All
		Gravel parameters
		All

[1]Significance level used for acceptance of null hyposthesis p<.10.
[2]Analyses were performed using SPSS (Hull and Nie 1981, Nie et. al 1975).
[3]Analyses were performed using methods described by Hollander and Wolfe 1973.

RESULTS

Intragravel Parameters

Temperature --Intragravel water temperature measured from the standpipes ranged from -0.5 to 12.2°C over the two-year study period (Table 2). Data from the intragravel thermographs indicated that water temperatures at and below 0° C were recorded from the last week of December to the second week of February (week 7 through week 13) in both years. The maximum daily temperature range was 7°C in the surface water and 3°C within the stream bed. Correlation between surface and intragravel water temperatures recorded weekly in the standpipes was very high (r=0.99, n=367). Differences between surface and intragravel water temperatures were tested for significance between redd and nonredd locations, between streams, over time,and among substrate depths, but none were found.

Dissolved Oxygen Concentration and Percent Oxygen Saturation -- Dissolved instream and intragravel oxygen (D.O.) concentrations ranged from 2.6 to 18.0 mg/l, and percent oxygen saturation ranged from 22 to 176 percent (Table 2). Intragravel D.O. averaged 10.3 mg/1, and stream water D.O. averaged 10.9 mg/1. Correlation between surface and intragravel dissolved oxygen concentration was high (r=0.90, n=265), as was correlation between surface and intragravel percent oxygen saturation (r=0.84, n=265). No significant

Table 2. Means, standard deviations and ranges of stream and intragravel water parameters from the second week of November through the second week of May, 1979-1980 and 1980-1981.

	1979-1980				1980-1981				Combined data from 1979-1980 and 1980-1981			
Parameter	$\bar{x}$	S.D.	Range	(N)	$\bar{x}$	S.D.	Range	(N)	$\bar{x}$	S.D.	Range	Total (N)
Stream water temperature (C^{o})	4.2	2.5	0-10.0	(129)	5.3	3.5	-0.5 - 12.2	(158)	4.8	2.8	-0.5 - 12.2	(287)
Intragravel water temperature (C^{o})	4.1	2.5	0-10.0	(129)	5.2	3.5	-0.5 - 12.2	(158)	4.7	2.9	-0.5 - 12.2	(287)
Stream water dissolved oxygen (D.O.) (mg/1)	11.5	2.5	6.0 - 17.2	(110)	10.5	1.8	5.8 - 18.0	(158)	10.9	2.1	5.8 - 18.0	(268)
Intragravel water D.O. (mg/1)	10.5	2.4	2.6 - 14.2	(110)	10.2	18.0	3.6 - 14.2	(158)	10.3	2.1	2.6 - 14.2	(268)
Percent saturation of stream D.O. (%)	102.9	25.0	52 - 176.0	(110)	95.3	12.9	56 - 166	(158)	98.1	18.3	52 - 176	(268)
Percent saturation of intragravel D.O. (%)	93.3	23.6	22 - 145	(110)	92.2	13.3	35 - 130	(158)	80.3	19.3	22 - 145	(268)

differences were found between redd and nonredd locations, between streams, over time, and among depths when the differences between stream and intragravel dissolved oxygen levels were tested. The analysis of differences in percent oxygen saturation between surface and subsurface readings also showed no significant differences.

Permeability --Permeability ranged from 250 to 149,350 cm/hr and averaged 6,150 cm/hr (Table 3). When paired redd and nonredd values were contrasted using weekly data, the permeability in redds was significantly greater than in nonredds sites and averaged 9,100 cm/hr and 8,100 cm/hr, respectively (Wilcoxon Rank Sum test; $p<0.02$). No significant difference in permeability was found between redd and nonredd locations in the depth-profiled data set, or between streams for either data set. When weekly permeability values were tested over time, using time periods 1-5, no significant differences were found for either field season. Significant differences were found among sample dates for the sites profiled during the 1979-1980 field season; the permeabilities recorded during week 21 were significantly less than those measured during weeks 8 and 17, which were not different from each other (Friedman Rank Sum Multiple Comparison test; $p<0.01$) (Table 4). No difference between weeks was found in the 1980-1981 profiled-site data. Permeability decreased significantly with depth. The permeability recorded within the top 10 cm of the substrate was significantly greater than that recorded

Table 3. Means, 95% confidence intervals (CI), and range of permeability (K_{10}) and apparent velocity (V) measured weekly, November - May 1979-1980 and 1980-1981.

	1979-1980				1980-1981				Combined data from 1979-1980 and 1980-1981			Total
	$\bar{x}$	CI[1]	Range	(N)	$\bar{x}$	CI[1]	Range	(N)	$\bar{x}$	CI[1]	Range	(N)
Permeability cm/hr[2]	5000	4550 - 5550	1200 - 34,900	(125)	7150	6300 - 8200	250 - 149,350	(157)	6150	5600 - 6700	250 - 149,350	(282)
Apparent[3] velocity cm/hr	40	30-50	0-810	(115)	20	10-30	0-1000	(140)	30	20-40	0-1000	(255)

[1]Confidence limits are calculated CI = antilog $\left(\ln K_{10} + t_{(n-1)}\sqrt{\dfrac{\text{Variance of transformed sample}}{n}}\right)$ (Elliot 1971)

[2]Reported values are antilog of $\ln K_{10}$

[3]Reported values are antilog of $\ln(V + 1)$

Table 4. Comparison of mean values of permeability and mean apparent velocity by sample date, December 1979 - April 1980.[1]

	Sample date in weeks		
	17	8	21
Permeability cm/hr (p = .01)[3]	11900	9100	3750
Apparent velocity cm/hr (p = .05)	30	30	20

[1] Values underlined do not differ significantly (Friedman Rank Sum Multiple Comparison test).

[2] Reported values are antilog of $\ln K_{10}$ and $\ln(V+1)$

[3] Significance level

at 10 to 20- or 20 to 30-cm layers (Friedman Rank Sum Multiple Comparison test; $p<0.01$) (Table 5).

The correlations of permeability with apparent velocity, dissolved oxygen concentration, and instream flows, using weekly data, were generally low, although some significant correlations were found (Table 6). When data from the profiled sites were tested, permeability was correlated with apparent velocity ($r=0.448$, $p<0.05$). When data were divided by depth, and tested again, this relationship held only for the 0 to 10-cm layer ($r=0.595$, $p<0.01$) (Table 7).

Apparent Velocity --Apparent velocities, measured at weekly intervals, averaged 30 cm/hr and ranged from 0 to 1000 cm/hr (Table 3). No significant differences were found between redd and nonredd locations or between streams. Apparent velocities, measured at weekly intervals, did not differ significantly between time periods for either field season. Significant differences were found during the 1979-1980 field season, where the mean apparent velocity recorded during week 21 was less than that recorded during weeks 8 or 17 (Friedman Rank Sum Multiple Comparison test; $p<0.01$) (Table 4). Apparent velocity decreased with depth; the mean velocity recorded within the 0 to 10-cm layer was significantly greater than mean velocity in either the 10 to 20- or the 20 to 30-cm layers (Friedman Rank Sum Multiple Comparison test; $p<0.05$)(Table 5). Correlations

Table 5. Comparison of mean values of permeability (K_{10}) and apparent (V) velocity by depth strata from profiled sites, December-April, 1979-1980 and 1980-1981.[1,2]

	Depth Strata		
	0-10 cm	10-20 cm	20-30 cm
Permeability cm/hr	10800	5300	3250
Apparent velocity cm/hr	60	10	0

[1]Values underlined do not differ significantly (Friedman Rank Sum Multiple Comparison test; p=.01)

[2] Reported values are antilog of $\ln K_{10}$ and $\ln(V+1)$.

Table 6. Spearman's rank correlation matrix (r) of permeability, apparent velocity, instream water velocity and intragravel dissolved oxygen values, November-May, 1979-1980 and 1980-1981 (N=255).

	Permeability	Apparent velocity	Instream water velocity	Intragravel dissolved oxygen
Permeability	1.000	0.190[1]	-0.018	0.090[1]
Apparent velocity	---	1.000	0.061	0.081[1]
Instream water velocity	---	---	1.000	-0.187[2]
Intragravel dissolved oxygen	---	---	---	1.000

[1]Significant at 5% level.

[2]Significant at 1% level.

Table 7. Spearman correlation matrix (r) of permeability (K_{10}), apparent velocity (V), and gravel indices by depth strata.

	DEPTH STRATA							
	0-30 cm (N=71)		0-10 cm (N=24)		10-20 cm (N-24)		20-30 cm (N=23)	
	K_{10}	V	K_{10}	V	K_{10}	V	K_{10}	V
K_{10}	1.000	0.448[2]	1.000	0.450[1]	1.000	-0.110	1.000	0.165
V	0.448[2]	1.000	0.450[2]	1.000	-0.110	1.000	0.165	1.000
Geometric mean diameter	0.036	0.004	-0.325	-0.216	-0.176	0.303	0.351	-0.352
Sorting coefficient	0.008	-0.200	0.077	-0.135	0.230	0.498[1]	0.205	0.002
Fredle index	-0.006	0.079	-0.297	-0.124	-0.166	0.431[1]	0.288	-0.262
Percent finer than 2.00 mm	-0.006	-0.117	0.170	0.110	0.176	-0.491[1]	-0.277	0.120
Porosity	0.057	0.037	-0.138	0.076	0.100	-0.227	0.206	0.268
Water velocity	-0.079	0.02[1]	0.595[2]	0.144	0.014	0.519[2]	0.170	0.663[2]

[1]Significant at 5% level

[2]Significant at 1% level

between apparent velocity and instream flow and between apparent velocity and intragravel dissolved oxygen were generally low (Table 6). The high correlation between instream flow and apparent velocity recorded at the 10 to 20- and 20 to 30-cm layers may be the result of low variation in the apparent velocity recorded at those depths.

Gravel Parameters

All the indices computed to characterize gravel composition varied widely (Table 8, Appendices 30-34). Nonparametric analyses did not reveal any significant differences between the variables tested (redd-nonredd, stream, time, depths, and standpipe-no standpipe). Correlations among calculated gravel indices were generally high, ranging from 0.616 to 0.957 (n=126) (Table 9). There was little significant correlation between gravel indices and either permeability or apparent velocity (Table 7). In order to determine if gravel particle diameter classes were log-normally distributed, cumulative percent composition was regressed on the log of particle diameter class(Tappel and Bjornn 1983). For the 126 core layers collected, the average coefficient of determination (r^2) was 0.862 and coefficients ranged from 0.60 to 0.98, indicating that the data approximated a log-normal distribution.

Table 8. Means, confidence intervals (CI), and ranges of gravel indices calculated from freeze cores, December - April, 1979-1980 and 1980-1981.

	1979-1980 (N=57)			1980-1981 (N=69)			Combined data over both years 1979-1980 and 1980-1981 (N=126)		
	$\bar{x}$[1]	95% CI[2]	Range	$\bar{x}$[1]	95% CI[2]	Range	$\bar{x}$[1]	95% CI[2]	Range
Geometric mean diameter (mm)	11.8	10.2 - 13.7	2.6 - 31.4	12.9	11.35 - 14.7	3.6 - 53.2	12.45	11.2 - 13.6	2.6 - 53.5
Sorting coeffecient	2.8	2.5 - 3.2	1.4 - 7.4	2.7	2.50 - 3.0	1.2 - 6.5	2.77	2.6 - 3.0	1.2 - 7.4
Fredle index	4.2	3.2 - 5.40	0.60 - 20.4	4.7	3.83 - 5.9	0.60 - 44.2	4.47	3.8 - 5.3	0.6 - 44.2
Porosity (%)	19.1	17.6 - 20.8	7.4 33.3	18.4	17.1 19.7	9.1 - 37.2	18.70	18.0 - 20.1	7.4 - 37.2
Fine $\leq$ 2.00 mm (%)	17.4	15.6 19.5	5.8 47.3	17.0	15.5 - 18.7	5.8 - 39.6	17.20	16.3 - 18.2	5.8 - 47.3

[1]Reported values are the antilog of transformed values i.e., antilog (lndg).

[2]Confidence intervals $CI_x = \text{antilog}\left(\ln x + t_{(n-1)}\sqrt{\frac{\text{Variance of transformed sample}}{n}}\right)$

Table 9. Spearman correlation matrix (r) of gravel indices from freeze core samples (N=126).[1]

	Geometric mean diameter	Sorting coefficient	Fredle index	Fines (≤2.00mm)	Porosity
Geometric mean diameter (mm)	1.000[1]	-0.770	0.957	-0.887	-0.723
Sorting coefficient		1.000	-0.922	0.872	0.616
Fredle index			1.000	-0.934	-0.719
Fines ≤2.0 mm (%)				1.000	0.692
Porosity (%)					1.000

[1]All correlations were significant at 5% level.

Egg Deposition and Distribution

The number of eggs and areas of their distribution were recorded from 9 redds in 1979-1980 and from 14 redds in 1980-1981. The depth of eggs found in freeze cores ranged from 2 to 18 cm. The number of eggs in the freeze cores ranged from 0 to 90 and averaged 24 (Table 10). Most of the eggs (90 percent) were collected from the surrounding gravel after the core was removed. The areas of egg deposition estimated from the excavated redds were small, ranging from .01 to .20m^2. Depth of egg deposition at the excavation sites ranged from 3 to 18 cm; the number of eggs varied from 20 to 426, and averaged 136 (Table 11). Estimates of egg loss were obtained from five of the excavated redds which were replanted and then re-excavated at a later date. Three redds were re-excavated after 6 weeks and two after 10 weeks. The loss of eggs averaged 4.5 percent per week (Table 12).

DISCUSSION

Intragravel Parameters

Two of the most important water quality variables affecting development and survival of brown trout larvae are temperature and dissolved oxygen concentration. Intragravel water temperatures at or below 0°C were recorded during a 7-week period starting the last week of December. On at least four occasions during January and

Table 10. Number and depth of eggs collected during freeze coring, January-April 1980 and December-March 1980-1981.

Year	Week	Number of eggs in core	Depth of eggs collected (cm)	Number of eggs in seine	Total number of eggs
1980					
Redd #					
9	8	17	3-18	0	17
15		4	4-15	19	23
7		3	5	2	5
10	17	0	-	37	37
14		0	-	6	6
5		0	-	6	6
11	21	0	-	0	0
13		0	-	0	0
2		1	4	67	68
1980-1981					
Redd #					
18	4	4	2	10	16
22		1	5	58	59
24		2	2	16	18
19	11	12	6	9	21
5		0	-	90	90
8		4	9	21	25
10	17	0	-	24	24
13		0	-	21	21
17		0	-	4	4
28		0	-	14	14
Mean		2.4		21.6	24.0

Table 11. Area of deposition, depth and number of brown trout eggs from excavated redds.

Year	Week	Area of egg deposition (m^2)	Range of egg depth (cm)	Number of eggs
1980-1981				
Redd #				
14	1	0.08	8-15	153
23	1	0.20	8-18	426
2	2	0.01	4- 5	20
8	7	0.06	4- 7	85
12	7	0.11	3-12	116
1981-1982				
Redd #				
10	2	0.07	3- 9	316
7	2	0.02	5-12	44
12	2	0.03	7-14	97
29	2	0.03	3-10	114
21	8	0.04	5- 9	49
16	8	0.01	4- 8	76
Mean		$0.06m^2$		136

Table 12. Number and percent of eggs lost from excavated, planted, and re-excavated redds, November-April 1980-1981 and 1981-1982.

Year	Week excavated	Eggs (No.)	Week re-excavated	Weeks past	No. eggs recovered	Total % eggs lost	Mean % egg lost per week
1980-1981 Redd #							
14	1	153	7	6	89	42	7.0
23	1	426	7	6	366	14	2.3
8	7	85	17	10	29	66	6.6
12	7	116	17	10	92	19	1.9
1981-1982 Redd #							
10	2	316	8	6	226	29	4.8
					Mean egg loss/week =		4.5

February in both years, thick ice in the standpipes prevented sampling. Previous reports from western North Carolina have related the presence of anchor ice to increased larval mortality (Harshbarger and Porter 1979, Dechant 1980). Lennon (1967) attributed low survival of brook char (Salvelinus fontinalis) fry in the Great Smoky Mountains National Park to the formation of anchor ice, and the subsequent dewatering and freezing of redds. Clearly, low water temperatures may have a significant impact on intragravel survival of brown trout embryos in this region.

Several factors indicate that intragravel water flow is primarily of surface rather than groundwater origin: (1) high correlation between stream and subsurface water temperatures, (2) high correlation between stream and subsurface dissolved oxygen, (3) lack of significant increase in water temperature with depth in the substrate, and (4) lack of significant decrease in dissolved oxygen with depth in the substrate. Studies that have recorded changes in water temperature and dissolved oxygen with depth have related these changes to groundwater flow (Sheridan 1962, Hansen 1975, Witzel and McCrimmon 1983). Unlike brook char, brown trout avoid spawning in areas of high groundwater flow (Witzel and McCrimmon 1983). This may explain the lack of change in temperature and dissolved oxygen concentration with depth in my study. However, without identified areas of groundwater inflow in probable spawning gravels, selection or avoidance of these sites by brown trout could not be tested.

Dissolved oxygen concentrations measured in this study appeared to be adequate for salmonid development. Dissolved oxygen concentrations often decrease during the period of embryo incubation (McNeil 1966, Ringler and Hall 1975, Turnpenny and Williams 1980), and this decline has been related to a decrease in apparent velocity (Coble 1961), a decrease in permeability (Sheridan 1962), and/or an increase in fine sediments (Woods 1980). No such comparable relationships between dissolved oxygen and apparent velocity (r=0.08), permeability (r=0.09), or percent fines (r=0.10) were evident in my study.

Changes in intragravel water flow have been shown to be related to redd construction, time, and substrate size and arrangement (Cooper 1965). The lack of clear relationships between intragravel water flow and the variables redd-nonredd and time in my study may be due to the high variability of the stream substrates. Cooper (1965) has shown that the physical location of individual stones on the substrate surface can drastically affect intragravel flow patterns and velocities. In the small, isolated pockets of gravel where redds occur in the South Mills River drainage, the influence of local physical and hydraulic features may mask the effects of the independent variables tested.

Although the permeability of redds was significantly greater than that of nonredds at 10-cm depth at weekly sites, no significant differences were found among the profiled sites when they were tested either across all depths or only within the 0 to 10-cm layer. Redd construction has been shown to remove fine sediments from the redd site (Helle 1970) and to produce a streambed configuration more conducive to higher intragravel water flow than would be produced in undisturbed sites (Vaux 1962). In my study, this classic depression-mound configuration was quickly lost following the first spate. Observation of redds located in the 1980-1981 field season indicated that all visual cues to redd location were gone three weeks after initial discovery. The small area of streambed disturbed during brown trout redd construction (Table 11) and the low density of redds would also lessen the likelihood of significant changes in intragravel water flow due to alteration of the streambed configuration. If trout, by construction of the redd, do create a subsurface environment with greater permeability, this effect would be expected to decrease over time as bedload and suspended sediments infiltrate the redds and changes in discharge rearrange the streambed. I found no such time trends in my data. No significant differences in apparent velocity were noted between redd and nonredd sites for either the weekly or depth-profiled data sets.

Permeability and apparent velocity in spawning gravels have been shown to decrease significantly with time in several studies (Peters 1962, Wickett 1962, Reiser and Wesche 1977), and this has been related to the intrusion of fine sediments into the streambed (McNeil 1962). Working with steelhead trout (Salmo gairdneri) and chinook salmon spawning gravels, Reiser and White (1981) reported a decrease in permeability over time in a stream with a high percentage of fines in the substrate, but they did not find any change in another stream where the percent of fines was low. During a 7-week period, Peters (1962) recorded a 94-percent decrease in apparent velocity in a river section with a high sediment load and only a 17-percent decrease at an upstream site with low sediment loads. No clear trends in permeability or apparent velocity were found during my study. During 1979-1980, the permeability and apparent velocity recorded at the profiled sites in weeks 8 and 17 were significantly higher than in week 21, while no decrease over time was noted at weekly-measured sites. One possible explanation for the significant decrease at the profiled sites may be related to site variation. Another explanation for the lack of consistent results between data sets may be related to the impact of sampling techniques on the subsurface environment. In the first data set, standpipes were left at sample sites for the 25-week study period. During this time, the pipes may have been jarred occasionally by high water, debris, and/or moving surface ice, thereby disturbing the subsurface environment. The presence of the standpipes may have altered localized flow regimes and sediment deposition around the sample sites.

Both permeability and apparent velocity decreased dramatically with depth beneath the streambed surface (Table 5). The low apparent velocities recorded within the 10 to 20- and 20 to 30-cm layers may affect the survival of brown trout eggs (Phillips and Campbell 1961, Rieser and Bjornn 1979), but within the top 10 cm of the streambed, where most eggs were deposited, apparent velocities were adequate for larval development (60 cm/hr).

Gravel Parameters

Substrate composition is one of the most important features of the gravel environment. Substrate particle size, arrangement, and morphology have all been shown to influence survival of salmonid embryos (Meehan and Swanston 1977, Iwamato et al. 1978). Streambed composition is determined by a complex interaction of physiographic and hydrologic factors. In my study, when gravel parameters were related to the independent variables of redd formation, time, stream, and depth within the streambed, the observed variation could not be attributed to any single factor. Variability of the calculated indices both within and between sites may have obscured the effect of the factors tested. Large variation in substrate composition has been reported by other investigators. Adams and Beschta (1980) found significant differences in percent of fine sediment among 16 cores collected within a 1.44-m^2 area of riffle of uniform composition. Platts et al. (1979) reported a two-fold variation in geometric mean diameter of gravels from different areas within a chinook salmon redd. Substrate parameters also vary greatly in both time and space. My sample sites were generally located in isolated patches of gravel, where large spatial variation would be expected. The lack of any significant differences among depths tested indicates that the substrate was poorly sorted; stream substrates could be eroded during a period of high flow, then quickly redeposited before particles could be differentially transported.

Survival of salmonid embryos to emergence has been defined by many authors as a function of gravel composition (McNeil 1964, Peterson 1978, Shirazi and Seim 1979). Using the relationship between larval survival and gravel composition as defined by various researchers, my survival estimates varied from 14 to 98 percent, and averaged 70.7 percent (Table 13). Previous estimates reported from western North Carolina range from 0-50 percent (Dechant 1979, Harshbarger and Porter 1982).

Intrusion of fine sediment into the substrate after spawning would be a function of hydrologic variables such as discharge, water depth and velocity, sediment load (Einstein 1968), and substrate morphology (Meehan and Swanston 1977). Under stable flow conditions, fine sediment can effectively seal off lower levels of the streambed (Beschta and Jackson 1979) and prevent embryo movement and emergence (Koski 1966, Bjornn 1968, Witzel and MacCrimmon 1981). There was no indication in my study that fines accumulated in the top layer of substrate. Restriction of movement by pre-emergent fry has been reported in gravel with a geometric mean diameter less than 11.8 mm (Witzel and MacCrimmon 1983) or in gravel containing more than 30 percent fine sediment (<4.00 mm) (Bjornn 1968). The geometric mean diameter of particles in the 0 to 10-cm layers in my study was

Table 13. Estimates of salmonid embryo survival, based on substrate composition of Poplar Creek and South Mills River samples as generated from cited references.

Index	Mean Poplar Creek and South Mills River gravel indices	Estimated survival (%)	Salmonid species	Reference
Geometric mean diameter (mm)	12.38	60	Coho Cutthroat Sockeye Steelhead	Sharazi and Seim 1979
Fredle index	4.47	63 83	Coho Steelhead	Lotspeich & Everest 1981
Fines $\leq$3.30mm	21.7	72	Coho	Koski 1966
Fines $\leq$2.00mm	17.2	90	Brook Char	Hausle & Coble 1976
Fines $\leq$0.84mm	13.2	80 98	Coho Brook Char	Hall and Lantz 1969 West et al. 1982
Sand $1.00 \leq x \leq 3.30$mm	8.5	87 97	Steelhead Coho	Hall and Lantz 1969
% $\leq$0.84mm and % $\leq$9.50m	13.3 57.5	29 14	Steelhead Chinook	Tappel and Bjornn 1983

14.8 mm, and fines (<4.00 mm) comprised 24 percent of the material, indicating that this subsurface environment was suitable for larval emergence.

The impact of salmonid spawning on gravel composition would increase as the area and/or density of redds increased. Greater average particle size of spawning gravel after redd excavation has been reported for large chinook salmon redds (Platts et al. 1979) and for pink salmon spawning riffles where redd density is high (Helle 1970). The apparent consistency in gravel composition after spawning by brown trout in my study corroborates similar results reported by Ottaway et al. (1981).

When cores were taken from sites with standpipes, the core probe was inserted into the void created by removal of a standpipe, but no significant differences in substrate composition were found between these two core types. Porosity would be the parameter most likely affected by removal of the standpipe. The fact that removal of the standpipe did not significantly alter porosity values would seem to indicate that either 1) the variable is not sensitive enough to detect changes or 2) porosity remained constant before and after rearrangement of the substrate around the standpipe. The effect of substrate arrangement on all the indices needs to be tested to determine the sensitivities of these measures to change.

Egg Deposition and Distribution

The small number of eggs collected from most of the sampled redds may have resulted from: (1) loss of eggs from disintegration, (2) redd washout from high stream flows, (3) multiple spawning by a single female, or (4) sampling techniques. Data from re-excavated redds indicated an average decrease in egg numbers of 4.5 percent per week (Table 12). Similar losses have been reported in previous studies. McNeil et al. (1964) reported a loss of 65 percent of nonviable pink salmon ova from a southeast Alaskan stream after a 12-week period (5.4-percent loss/week). Hausle and Coble (1976) recorded a loss of 24 percent of brook char eggs after 13 weeks (1.8-percent loss/week).

Losses of embryos due to high water during the incubation period have been reported by several investigators. McNeil (1962) reported a 40-percent loss of pink salmon embryos following high water. Dechant (1980) recorded the loss of 14 of 22 redds as a result of high water and/or anchor ice. With egg deposition limited to the top 10 cm of the substrate, washout from high discharge may be a major factor in determining the number of embryos remaining in the gravel. In the southern Appalachians, intense winter storms can produce large fluctuations in discharge. Rainfall data from the Pisgah National Forest, approximately 5 km away, indicated storms of more than 5 cm of rain/24 hr occurred five times during 1979-1980 and twice in 1980-1981 during the study period. The absence of eggs in two of nine redds cored during 1979-1980 may have indicated washout of these redd sites.

The wide variation in numbers of eggs collected from the cored and excavated redds may indicate the formation of multiple redds by a single female brown trout and/or a wide range in size of spawning females. Multiple spawning has been reported for brook char (Needham 1961), steelhead trout (Reingold 1965, Orcutt et al. 1968), and brown trout (Hobbs 1948, Hardy 1963). The fecundity of female brown trout calculated from the size of brown trout observed over the redds(20-60 cm) was estimated to range from 200 to 6000 eggs/female (Carlander 1969), indicating that potential egg deposition per redd could vary widely.

Exact relocation of redds was difficult due to the small area of egg deposition. Hand sifting of gravels (from within the Hess sampler and within the area of freeze cores) may have destroyed many fry.

Recommendations for Management and Further Research

Results of this study indicate that the subsurface environment of the spawning sites was suitable for development and emergence of brown trout fry. Factors that may affect larval survival are water temperature and the depth of egg deposition. Water temperatures of $0^{o}C$ and colder are common occurrences during winter in these streams. Fisheries managers should therefore expect major losses in young-of-the-year trout following cold winters. When the depth of egg deposition is shallow, redds can be easily disrupted by fall, winter, or spring rain storms. Management activities that affect water yields should also be considered in light of the increased probability of redd washout with higher flows.

Due to the lack of significant differences between redd and nonredd locations with respect to the subsurface environment, this study indicates that actual redd sites need not be monitored. A fisheries biologist familiar with the gravels selected by brown trout could locate potential spawning sites for study. The inherent variability of these sites, however, will complicate assessment of the spawning environment. Any sampling design for monitoring spawning habitat must consider the variation within and between sites.

The lack of significant differences in the parameters tested over the period of egg development indicates that sampling could be done at any time from November to March. Changes in substrate composition throughout the year have been observed in other regions, and these changes were related to periods of high water,during which fines were removed and stream substrates were redistributed (Adams and Beschta 1980). In the southern Appalachians, the onset of peak flows usually begins in early spring (Douglass 1974). If resource managers or fisheries biologists want to monitor the subsurface environment, sampling should take place before these periods of high water.

The lack of any clear relationship between substrate parameters and intragravel water flow is not surprising, considering the highly variable nature of the stream environment and the large number of external variables that can influence subsurface water flow. Future work should focus on the hydrologic and physiographic factors that create temporal and spatial variability in the subsurface environment. Defining the local and watershed parameters that affect both the quality and quantity of suitable spawning habitat in southern Appalachian streams will be important if fisheries biologists are to mitigate the impact of land use activities on this habitat component. Refinement of sampling equipment will also be needed so that gravel and intragravel parameters can be quantified with greater accuracy.

SUMMARY AND CONCLUSIONS

1. The gravel and intragravel characteristics at different depths within and adjacent to brown trout redds were studied in two North Carolina streams during 1979-1980 and 1980-1981.
2. Intragravel water temperature, dissolved oxygen concentration,and percent oxygen saturation within the gravel environment closely paralleled surface water values.
3. Zero and subzero intragravel water temperatures are common in southern Appalachian streams and may have a significant impact on intragravel survival of brown trout embryos.
4. Permeability and apparent velocity in redd and nonredd sites were highly variable.
5. Data were collected 10 cm below the surface of the streambed to test for significant differences in permeability and apparent velocity between streams, between redd and nonredd sites, and among time periods. Permeability in redds may be significantly greater than in nonredds. No differences in apparent velocity were found between redds and nonredd locations. Significant differences in these parameters over time were not found.
6. Permeability and apparent velocity decreased significantly with depth beneath the substrate surface.

7. Geometric mean diameter, sorting coefficient, fredle index, percent fine sediment ($\leq$2.00 mm), and porosity were not sigificantly different between redd and nonredd locations, among sample dates, or among depths.

8. No significant correlation was found between either permeability or apparent.velocity and geometric mean diameter, sorting coefficient, fredle index, or percent fines.

9. Large natural variations in the subsurface environment may have masked the effects of the factors studied.

10. Brown trout generally deposited their eggs within the top 10 cm of the substrate where the probability of washout may be a major factor in determining survival to emergence of fry.

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APPENDIX TABLES AND FIGURES

Appendix 1. Sample week by calendar dates for the two study periods 1979-1980 and 1980-1981.

Sample week	1979-1980	1980-1981
1	18-24 Nov. 1979	16-22 Nov. 1980
2	25 Nov. -1 Dec.	23-29 Nov.
3	2-08 Dec.	30 Nov. -6 Dec.
4	9-15 Dec.	7-13 Dec.
5	16-22 Dec.	14-20 Dec.
6	23-29 Dec.	21-27 Dec.
7	30 Dec. -5 Jan. 1980	28 Dec.-3 Jan. 1981
8	6-12 Jan.	4-10 Jan.
9	13-19 Jan.	11-17 Jan.
10	20-26 Jan.	18-24 Jan.
11	27 Jan. -2 Feb.	25-31 Jan.
12	3-09 Feb.	1-07 Feb.
13	10-16 Feb.	8-14 Feb.
14	17-23 Feb.	15-21 Feb.
15	24 Feb. -1 Mar.	22-28 Feb.
16	2-08 Mar.	1-07 Mar.
17	9-15 Mar.	8-14 Mar.
18	16-22 Mar.	15-21 Mar.
19	23-29 Mar.	22-28 Mar.
20	30 Mar. -5 Apr.	29 Mar. -4 Apr.
21	6-12 Apr.	5-11 Apr.
22	13-19 Apr.	12-18 Apr.
23	20-26 Apr.	19-25 Apr.
24	27 Apr. -3 May	26 Apr. -2 May
25	4-10 May	3-10 May

Appendix 2. Intragravel and instream water temperatures (C°) recorded at redd and nonredd sites on Poplar Creek and South Mills River, 3rd week of November 1979 through 2nd week of May 1980.[1]

				Time Periods 1			2			3			4	
Stream	Site	Redd	Wk.	Intra-Gravel	In-Stream	Wk	Intra-Gravel	In-Stream	Wk	Intra-Gravel	In-Stream	Wk	Intra-Gravel	In-Stream
Poplar Creek	3	Redd	1			6	3.9	4.0	11	2.0		16	2.0	
			2			7	4.5		12	ice		17	5.0	
			3	4.5	5.0	8	4.0		13	0.0		18	5.0	
			4	7.0		9	6.0		14	0.0		19	7.5	
			5	1.5		10	4.0		15	1.0		20	9.9	
	3	Non-Redd	1			6	3.9	4.0	11	2.0		16	2.0	
			2			7	4.5		12	ice		17	5.0	
			3	4.5	5.0	8	4.0		13	0.0		18	5.0	
			4	7.0		9	6.0		14	0.0		19	7.5	
			5	1.5		10	4.0		15	1.0		20	9.9	
	6	Redd	1			6	4.0		11	2.0		16	2.0	
			2			7	3.5		12	0.0		17	2.0	3.0
			3	4.0		8	4.5		13	.5		18	A	
			4	7.5		9	6.0		14	3.0		19	A	
			5	2.0		10	5.0		15	1.5		20	A	
	6	Non-Redd	1			6	4.0		11			16		
			2			7	3.5		12			17		
			3	4.0		8			13			18		
			4	7.5		9			14			19		
			5	2.0		10			15			20		
South Mills River	12	Redd	1			6			11	5.0		16	5.0	
			2			7			12	ice		17	5.0	
			3			8	4.0		13	3.0		18	7.0	
			4			9	4.0		14	3.0		19	8.0	
			5			10	5.0		15	2.2		20	10.0	
	12	Non-Redd	1			6		4.0	11	5.0		16	5.0	
			2			7			12	ice		17	5.0	
			3			8	4.0		13	3.0		18	7.0	
			4			9	4.0		14	3.0		19	8.0	
			5			10	5.0		15	2.0		20	10.0	

A = Equipment breakdown.
B = Standpipe knocked over.
Ice = Ice prevented measurement.

[1]In those cases where no instream value is listed, intragravel and instream temperatures were identical.

Appendix 3. Intragravel and instream water temperatures (C°) recorded at redd and nonredd sites on Poplar Creek and South Mills River, 3rd week of November 1980 through 2nd week of May 1981.[1]

			Time Periods 1			2			3			4			5		
Stream	Site	Redd	Wk.	Intra-Gravel	In-Stream	Wk	Intra-Gravel	In-Stream	Wk	Intra-Gravel	In-Stream	Wk	Intra-Gravel	In-Stream	Wk	Intra-Gravel	In-Stream
Poplar Creek	21	Redd	1	3.0		6	0.5		11	2.0		16			21	8.0	
			2	5.0		7	3.75		12	ice		17	4.5		22	10.0	
			3	3.5	4.2	8	.75		13	2.0		18	3.0		23	11.0	11.2
			4	10.1		9	ice		14	4.8		19	4.0		24	12.2	12.5
			5	4.5		10	-0.5		15	4.0		20	9.5		25	12.0	
		Non-Redd	1	3.0		6	0.5		11	2.0		16			21	8.0	
			2	5.0		7	3.75		12	ice		17	4.8	5.0	22	10.0	
			3	3.5	4.2	8	0.8		13	2.0		18	3.0		23	11.0	11.2
			4	10.1		9	ice		14	5.0		19	4.0	4.2	24	12.0	
			5	4.5		10	-0.5		15	4.0		20	9.5		25	12.0	
	33	Redd	1	3.0	4.0	6	0.0		11	2.0		16	A		21	9.5	9.0
			2	4.8		7	3.8		12	ice		17	4.9	5.0	22	9.8	10.0
			3	3.5		8	0.8		13	1.0		18	4.3	5.0	23	11.8	12.0
			4	7.0		9	ice		14	5.0		19	4.2		24	12.3	
			5	4.0		10	-0.5	0.5	15	4.3		20	9.2	9.5	25	11.5	
		Non-Redd	1	[illegible].0	4.0	6	0.0		11	2.0		16	A		21	8.8	
			2	4.8		7	3.8		12	ice		17	4.0	5.0	22	9.8	10.0
			3	3.5		8	0.5		13	4.8		18	4.9	5.0	23	11.8	12.0
			4	7.0		9	ice		14	5.0		19	4.3		24	12.3	
			5	4.0		10	-0.5		15	4.3		20	9.2	9.5	25	11.5	

A = Equipment breakdown.
B = Standpipe knocked over.
Ice = Ice prevented measurement.

[1]In those cases where no instream value is listed, intragravel and instream temperatures were identical.

Appendix 4. Intragravel and instream dissolved oxygen (mg/l) recorded at redd and nonredd sites on Poplar Creek and South Mills River, 3rd week of November 1979 through 2nd week of May 1980.[1]

				Time Periods										
				1			2			3			4	
Stream	Site	Redd	Wk.	Intra-Gravel	In-Stream	Wk	Intra-Gravel	In-Stream	Wk	Intra-Gravel	In-Stream	Wk	Intra-Gravel	In-Stream
Poplar Creek	3	Redd	1			6	11.19	11.4	11	6.5	8.1	16	8.8	11.0
			2			7	13.2	13.2	12	ice		17	13.2	17.2
			3	11.6	11.6	8	12.1	11.3	13	10.6	11.0	18	A	
			4	9.8	9.8	9	10.6	11.3	14	A	A	19	A	
			5	11.9	12.0	10	11.6	12.6	15	11.2	11.8	20	A	
	3	Non-Redd	1			6	11.4	11.4	11	6.5	8.1	16	8.7	11.0
			2			7	13.2	13.2	12	ice		17	13.2	17.2
			3	11.4	11.4	8	12.1	11.3	13	10.4	11.0	18	A	
			4	10.0	10.0	9	10.6	11.3	14	A		19	A	
			5	11.3	12.0	10	10.4	10.6	15	10.8	11.8	20	A	
	6	Redd	1			6	A		11	7.2	9.8	16	7.8	9.5
			2			7	13.2	13.2	12	12.2	12.6	17	2.6	6.0
			3	11.1	11.1	8	8.5	10.2	13	12.6	12.6	18	A	
			4	10.0	10.0	9	10.6	11.3	14	A		19	A	
			5	11.3	12.0	10	8.5	8.9	15	12.0	12.3	20	A	
	6	Non-Redd	1			6	A		11			16		
			2			7			12			17		
			3	11.1	11.1	8			13			18		
			4	9.4	9.4	9			14			19		
			5	11.6	11.6	10			15			20		
South Mills River	12	Redd	1			6			11	7.2	8.4	16	7.2	13.6
			2			7			12	ice		17	A	
			3			8	6.4	8.4	13	A		18	9.3	9.9
			4			9	A		14	11.5	11.6	19	9.3	10.2
			5			10	7.5	8.6	15	8.0	9.2	20	A	
	12	Non-Redd	1			6			11	6.4	8.4	16	11.4	13.6
			2			7			12	ice		17	A	
			3			8	6.4	8.4	13	A		18	9.3	9.9
			4			9	A		14	11.5	11.6	19	9.6	10.2
			5			10	7.6	8.6	15	8.0	9.2	20	A	

A = Equipment breakdown.
B = Standpipe knocked over.
Ice = Ice prevented measurement.

[1] In those cases where no instream value is listed, intragravel and instream temperatures were identical.

Appendix 5. Intragravel and instream water temperatures (C°) recorded at redd and nonredd sites on Poplar Creek and South Mills River, 3rd week of November 1980 through 2nd week of May 1981.[1]

				Time Periods														
				1			2			3			4			5		
				Intra-	In-		Intra-	In-		Intra-	In-		Intra-	In-		Intra-	In-	
Stream	Site	Redd	Wk.	Gravel	Stream	Wk	Gravel	Stream	Wk	Gravel	Stream	Wk	Gravel	Stream	Wk	Gravel	Stream	
Poplar Creek	21	Redd	1	11.2	11.8	6	12.4	12.4	1	12.1	12.0	16	A A		21	9.5	9.0	
			2	11.0	12.1	7	10.0	10.1	12	A	A	17	11.0	11.6	22	9.4	9.9	
			3	10.2	10.6	8	10.3	10.4	13	12.2	12.0	18	10.0	9.9	23	9.2	9.2	
			4	9.1	10.0	9	A	A	14	8.9	9.5	19	11.0	11.4	24	8.7	9.2	
			5	10.6	11.4	10	14.0	16.0	15	7.8	8.5	20	9.3	9.7	25	9.4	9.2	
		Non-Redd	1	11.2	11.6	6	12.4	12.6	11	12.1	12.2	16	A	A	21	9.6	10.0	
			2	11.0	12.1	7	10.8	10.8	12	A	A	17	10.6	11.2	22	9.4	9.9	
			3	10.2	10.6	8	10.4	10.6	13	12.3	12.0	18	10.2	9.8	23	9.2	9.2	
			4	9.1	10.0	9	A	A	14	7.9	8.9	19	11.4	11.6	24	9.1	9.2	
			5	10.0	11.2	10	13.0	13.2	15	8.8	8.8	20	9.8	9.1	25	9.5	9.2	
	33	Redd	1	9.2	11.7	6	12.2	12.0	11	12.4	12.2	16	A	A	21	9.8	9.9	
			2	11.4	12.1	7	11.0	10.8	12	A	A	17	10.2	11.0	22	9.0	9.3	
			3	9.0	11.0	8	3.8	6.4	13	11.8	11.8	18	10.6	11.2	23	9.1	9.3	
			4	6.1	6.3	9	A	A	14	6.8	7.4	19	10.2	11.6	24	8.9	9.2	
			5	9.6	10.2	10	13.1	12.1	15	10.8	11.2	20	9.6	9.9	25	9.2	9.6	
		Non-Redd	1	10.2	11.7	6	12.0	12.0	11	12.2	12.1	16	A		21	9.8	9.9	
			2	8.3	11.6	7	9.1	11.0	12	ice	ice	17	10.2	11.0	22	9.0	9.3	
			3	7.8	10.0	8	3.6	5.8	13	11.4	11.4	18	10.6	11.2	23	9.1	9.3	
			4	7.0	7.0	9	ice		14	7.2	7.4	19	10.2	11.6	24	8.9	9.2	
			5	10.2	10.4	10	12.1	13.1	15	11.6	11.2	20	9.6	9.9	25	9.2	9.6	
	7	Redd	1			6	12.4	12.4	11	13.2	13.2	16	9.8	10.2	21			
			2	11.8	12.2	7	9.4	9.4	12	ice		17	11.8	12.2	22			
			3	6.0	6.0	8	10.8	10.8	13	B		18	10.4	10.6	23			
			4	9.8	10.1	9	ice		14	8.1	8.6	19	10.8	11.1	24			
			5	11.5	11.5	10	13.2	13.2	15	B		20	B		25	9.0	9.6	
		Non-Redd	1			6	12.4	12.6	11	13.2	13.2	16	9.8	10.2	21			
			2	12.2	12.0	7	11.2	11.2	12	ice		17	11.8	12.1	22			
			3	7.0	6.3	8	9.2	10.0	13	B		18	10.4	10.6	23			
			4	10.0	10.1	9	ice		14	8.4	8.6	19	11.6	11.0	24			
			5	11.5	11.5	10	13.2	12.8	15	14.2	18.0	20	B		25			

A = Equipment breakdown.
B = Standpipe knocked over.
Ice = Ice prevented measurement.

[1]In those cases where no instream value is listed, intragravel and instream temperatures were identical.

Appendix 6. Intragravel permeability (K_{10}) cm/hr recorded at redd and nonredd sites on Poplar Creek and South Mills River, 3rd week of November 1979 through 2nd week of May 1980.

			Time Periods									
Stream	Site	Redd	Wk	1	Wk	2	Wk	3	Wk	4	Wk	5
Poplar Creek	3	Redd	1		6	13700	11	10150	16	7500	21	
			2		7	6050	12	ice	17	3250	22	
			3	9300	8	6650	13	2550	18	6750	23	
			4	5900	9	2850	14	6000	19	A	24	
			5	13150	10	10000	15	5950	20	1800	25	
		Non-Redd	1		6	1200	11	7250	16	3600	21	
			2		7	10450	12	ice	17	3600	22	
			3	7900	8	4750	13	6000	18	A	23	
			4	5900	9	5050	14	3500	19	3000	24	
			5	10750	10	10400	15	7500	20	2550	25	
	6	Redd	1		6	21200	11	7250	16	3600	21	
			2		7	2550	12	ice	17	3600	22	
			3	5500	8	6150	13	6000	18	A	23	
			4	3200	9	6850	14	3500	19	3000	24	
			5	4450	10	8300	15	7500	20	2550	25	
		Non-Redd	1		6	5200	11		16		21	
			2		7	7200	12		17		22	
			3	9700	8		13		18		23	
			4	4550	9		14		19		24	
			5	4850	10		15		20		25	
South Mills River	12	Redd	1		6		11	A	16	3600	21	
			2		7		12	ice	17	4200	22	
			3		8	6050	13	4850	18	4100	23	
			4		9	7150	14	6550	19	4350	24	
			5		10	7050	15	6700	20	2900	25	
		Non-Redd	1		6		11	A	16	2500	21	
			2		7		12	ice	17	4550	22	
			3		8	2150	13	6750	18	5900	23	
			4		9	6700	14	6600	19	4550	24	
			5		10	2300	15	2300	20	1950	25	

A = Equipment breakdown.
B = Standpipe knocked over.
Ice = Ice prevented measurement.

Appendix 7. Intragravel permeability (K_{10}) cm/hr recorded at redd and nonredd sites on Poplar Creek and South Mills River, 3rd week of November 1980 through 2nd week of May 1981.

			Time Periods									
				1		2		3		4		5
Stream	Site	Redd	Wk		Wk		Wk		Wk		Wk	
Poplar Creek	21	Redd	1	27400	6	3000	11	8300	16	A	21	7200
			2	5000	7	126800	12	ice	17	7100	22	4500
			3	6600	8	86000	13	5300	18	8700	23	6400
			4	21700	9	ice	14	6500	19	3600	24	6700
			5	2300	10	11100	15	111100	20	4500	25	7900
		Non-Redd	1	10200	6	7600	11	8400	16	A	21	9000
			2	5000	7	18800	12	ice	17	5800	22	9600
			3	12200	8	17200	13	5200	18	11700	23	5300
			4	19700	9	ice	14	10100	19	6500	24	15400
			5	13400	10	12400	15	11300	20	6300	25	19500
	33	Redd	1	1800	6	11700	11	8400	16	A	21	9000
			2	5000	7	18800	12	ice	17	5800	22	9600
			3	12200	8	17200	13	5200	18	11700	23	5300
			4	19700	9	ice	14	10100	19	6500	24	15400
			5	13400	10	12400	15	11300	20	6300	25	19500
		Non-Redd	1	900	6	8100	11	2050	16	A	21	6700
			2	5000	7	13100	12	ice	17	8500	22	4600
			3	2600	8	5800	13	8000	18	9500	23	3500
			4	5900	9	ice	14	8000	19	9950	24	9950
			5	400	10	13500	15	8900	20	24350	25	12350
South Mills River	7	Redd	1		6	8500	11	13150	16	6250	21	6700
			2	7100	7	7650	12	ice	17	8950	22	4650
			3	9400	8	8000	13	B	18	10100	23	3500
			4	10500	9	ice	14	9400	19	6950	24	9550
			5	12800	10	13250	15	B	20	B	25	12400
		Non-Redd	1		6	8500	11	12900	16	8350	21	B
			2	10900	7	11350	12	ice	17	12350	22	B
			3	7600	8	6500	13	B	18	9450	23	B
			4	8500	9	ice	14	8900	19	6800	24	B
			5	12500	10	5750	15	8050	20	B	25	B

A = Equipment breakdown.
B = Standpipe knocked over.
Ice = Ice prevented measurement.

Appendix 8. Intragravel apparent velocity (cm/hr) recorded at redd and nonredd sites on Poplar Creek and South Mills River, 3rd week of November 1979 through 2nd week of May 1980.

			Time Periods									
			1		2		3		4		5	
Stream	Site	Redd	Wk		Wk		Wk		Wk		Wk	
Poplar Creek	3	Redd	1		6	120	11	50	16	20	21	
			2		7	250	12	ice	17	0	22	
			3	280	8	30	13	A	18	20	23	
			4	270	9	20	14	20	19	A	24	
			5	70	10	20	15	20	20	10	25	
		Non-Redd	1		6	210	11	40	16	10	21	
			2		7	120	12	ice	17	20	22	
			3	70	8	30	13	A	18	10	23	
			4	50	9	20	14	10	19	30	24	
			5	70	10	70	15	60	20	20	25	
	6	Redd	1		6	20	11	100	16	90	21	
			2		7	10	12	ice	17	40	22	
			3	60	8	20	13	A	18	A	23	
			4	20	9	80	14	80	19	A	24	
			5	100	10	80	15	110	20	20	25	
		Non-Redd	1		6	120	11		16		21	
			2		7	90	12		17		22	
			3	70	8		13		18		23	
			4	90	9		14		19		24	
			5	100	10		15		20		25	
South Mills River	12	Redd	1		6		11	A	16	10	21	
			2		7		12	ice	17	10	22	
			3		8	20	13	10	18	20	23	
			4		9	10	14		19	10	24	
			5		10	10	15	10	20	10	25	
		Non-Redd	1		6		11	A	16	140	21	
			2		7		12	ice	17	180	22	
			3		8	10	13	A	18	80	23	
			4		9	40	14	70	19	0	24	
			5		10	50	15	110	20	0	25	

A = Equipment breakdown.
B = Standpipe knocked over.
Ice = Ice prevented measurement.

Appendix 9. Intragravel apparent velocity (cm/hr) recorded at redd and nonredd sites on Poplar Creek and South Mills River, 3rd week of November 1980 through 2nd week of May 1981.

Stream	Site	Redd	Wk	Time Periods 1	Wk	2	Wk	3	Wk	4	Wk	5
Poplar Creek	21	Redd	1	50	6	40	11	10	16	A	21	10
			2	20	7	30	12	ice	17	10	22	80
			3	A	8	30	13	50	18	50	23	10
			4	10	9	ice	14	60	19	60	24	20
			5	20	10	A	15	10	20	10	25	0
		Non-Redd	1	60	6	20	11	10	16	A	21	60
			2	0	7	30	12	ice	17	50	22	120
			3	A	8	30	13	50	18	20	23	10
			4	70	9	ice	14	60	19	100	24	30
			5	30	10	A	15	10	20	120	25	30
	33	Redd	1	0	6	20	11	50	16	A	21	20
			2	0	7	60	12	ice	17	30	22	20
			3	A	8	30	13	30	18	30	23	20
			4	A	9	ice	14	50	19	40	24	10
			5	10	10	A	15	410	20	50	25	0
		Non-Redd	1	0	6	0	11	0	16	A	21	0
			2	0	7	0	12	ice	17	10	22	0
			3	A	8	0	13	10	18	40	23	0
			4	A	9	ice	14	30	19	10	24	0
			5	0	10	30	15	10	20	10	25	10
South Mills River	7	Redd	1		6	20	11	120	16	960	21	B
			2	10	7	20	12	ice	17	960	22	B
			3	A	8	10	13	B	18	960	23	B
			4	A	9	ice	14	500	19	720	24	B
			5	30	10	110	15	B	20	B	25	B
		Non-Redd	1		6	10	11	100	16	1000	21	B
			2	150	7	60	12	ice	17	1000	22	B
			3	A	8	50	13	B	18	360	23	B
			4	A	9	ice	14	60	19	300	24	B
			5	20	10	30	15	60	20	B	25	B

A = Equipment breakdown.
B = Standpipe knocked over.
Ice = Ice prevented measurement.

Appendix 10. Intragravel water temperatures (C°) by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980.[1]

Sample Week	Depth Strata	Poplar Creek Site		South Mills River Site	
		9		15	
		Redd	Nonredd	Redd	Nonredd
8	0-10	3.5	3.5	3.0	3.0
	10-20	5.0	5.0	4.3	4.3
	20-30	4.8	4.8	5.0	--
		5		14	
		Redd	Nonredd	Redd	Nonredd
17	0-10	4.5	4.5	5.0	5.0
	10-20	5.5	5.5	5.0	5.0
	20-30	4.0	4.0	3.8	3.8
		2		13	
		Redd	Nonredd	Redd	Nonredd
21	0-10	7.0	7.0	8.0	8.0
	10-20	1.0	1.0	1.0	1.0
	20-30	8.0	8.0	9.0	9.0

[1]Instream water temperatures recorded were identical to intragravel measures in all cases.

Appendix 11. Intragravel water and instream dissolved oxygen concentrations (mg/l) by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980.

Sample Week	Depth Strata	Poplar Creek Site				South Mills River Site			
		9				15			
		Intragravel		Instream		Intragravel		Instream	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
8	0-10	8.4	8.4	9.4	9.4	7.2	7.2	7.2	7.2
	10-20	7.2	7.2	10.8	10.8	10.6	10.6[1]	10.5	10.5
	20-30	8.8	8.8	10.2	10.0	10.2	--	--	--
		5				14			
		Intragravel		Instream		Intragravel		Instream	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
17	0-10	7.0	6.5	9.2	9.2	8.5	8.1	12.0	12.0
	10-20	4.0	4.7	10.4	10.4	3.7	5.0	5.9	5.9
	20-30	1.9	2.1	11.4	11.4	7.2	7.5	10.3	10.3
		19				5		8	
		Intragravel		Instream		Intragravel		Instream	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
21	0-10	--	--	--	--	--	--	--	--
	10-20	9.5	9.5	10.2	10.2	9.5	8.4	9.8	9.8
	20-30	--	--	--	--	--	--	--	--

[1]Equipment breakdown.

Appendix 12. Intragravel permeability (cm/hr) by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980.

Sample Week	Depth Strata	Poplar Creek Site		South Mills River Site	
		9		15	
		Redd	Nonredd	Redd	Nonredd
8	0-10	23000	10700	15600	13500
	10-20	5500	3000	9700	2800
	20-30	6200	30100	6000	---[1]
		5		14	
		Redd	Nonredd	Redd	Nonredd
17	0-10	31500	23400	13800	11900
	10-20	20900	11700	2100	8400
	20-30	3000	4000	8900	3000
		2		13	
		Redd	Nonredd	Redd	Nonredd
21	0-10	8100	6600	3500	3500
	10-20	4000	3300	3000	3400
	20-30	2400	1900	3000	2200

[1]Equipment breakdown.

Appendix 13. Intragravel apparent velocity(cm/hr) by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980.

Sample Week	Depth Strata	Poplar Creek Site		South Mills River Site	
		9		15	
		Redd	Nonredd	Redd	Nonredd
8	0-10	16	6	250	5
	10-20	0	0	0	0
	20-30	1	0	0	---[1]
		5		14	
		Redd	Nonredd	Redd	Nonredd
17	0-10	180	120	20	10
	10-20	10	10	10	10
	20-30	10	20	10	0
		2		13	
		Redd	Nonredd	Redd	Nonredd
21	0-10	60	10	20	10
	10-20	20	20	20	20
	20-30	20	10	10	10

[1]Equipment breakdown.

Appendix 15. Intragravel and instream water temperatures (C°) by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980-1981.

Sample Week	Depth Strata	Poplar Creek Site				South Mills River Site			
		22							
		Intragravel		Instream[1]					
		Redd	Nonredd	Redd	Nonredd				
4	0-10	7.0	7.0	7.0	7.0				
	10-20	6.5	6.5	6.5	6.5				
	20-30	6.0	6.0	6.0	6.0				
		24				5			
		Intragravel		Instream[1]		Intragravel		Instream[1]	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
11	0-10	3.0	3.0	3.0	3.0	3.0	2.5	3.0	3.0
	10-20	-1.0	-0.5	-1.0	-1.0	2.5	2.5	2.5	2.5
	20-30	1.8	--[2]	1.0		3.0	2.5	2.5	2.5
		9				13			
		Intragravel		Instream[1]		Intragravel		Instream[1]	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
17	0-10	3.0	2.5	3.0	3.0	5.3	5.3	5.3	5.3
	10-20	2.5	2.5	2.5	2.5	2.5	2.6	2.5	2.5
	20-30	2.8	2.8	3.0	3.0	4.8	2.5	4.8	4.8
		17							
		Intragravel		Instream[1]					
		Redd	Nonredd	Redd	Nonredd				
17	0-10	5.3	5.3	5.3	5.3				
	10-20	3.0	3.0	3.0	3.0				
	20-30	3.0	3.0	3.0	3.0				

[1]In those cases where no instream value is listed intragravel and instream temperatures were identical.
[2]Equipment breakdown.

Appendix 16. Intragravel permeability (cm/hr) by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980-1981.

		Poplar Creek				South Mills River	
Sample Week	Depth Strata	Site		Site		Site	
		22					
		Redd	Nonredd				
4	0-10	10200	16800				
	10-20	2100	2100				
	20-30	790	100				
		24				5	
		Redd	Nonredd			Redd	Nonredd
11	0-10	11800	6100			5300	4800
	10-20	3500	8300			5300	7400
	20-30	4700	--[1]			2900	3000
		9		13		17	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
17	0-10	3600	3500	9500	5700	8000	8700
	10-20	2300	2400	3000	4400	3600	5100
	20-30	4100	2800	1800	500	2500	2100

[1]Equipment breakdown.

Appendix 17. Intragravel apparent velocity (cm/hr) by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980-1981.

		Poplar Creek				South Mills River	
Sample Week	Depth Strata	Site		Site		Site	
		22					
		Redd	Nonredd				
4	0-10	20	20				
	10-20	10	10				
	20-30	0	0				
		24				5	
		Redd	Nonredd			Redd	Nonredd
11	0-10	30	10			0	0
	10-20	20	10			0	0
	20-30	0	--[1]			0	0
		9		13		17	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
17	0-10	10	0	220	50	60	170
	10-20	--	--	10	0	0	0
	20-30	0	0	0	0	0	0

[1]Equipment breakdown.

Appendix 18. Geometric mean diameter (mm) of substrate in freeze cores by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980.

Sample Week	Depth Strata	Poplar Creek Site		Poplar Creek Site		South Mills River Site	
		7		9(S)[1]		15(S)	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
8	0-10	9.6	15.2	5.0	7.1	24.2	17.2
	10-20	2.6	16.2	9.8	7.2[2]	15.2	18.3
	20-30	17.0	13.7	13.3	--	20.6	12.3
		5(S)		10		14(S)	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
17	0-10	8.3	5.5	8.6	24.6	12.3	6.5
	10-20	5.5	11.4	14.6	6.4	9.2	4.6
	20-30	19.5	16.2	31.4	5.3	8.1	7.7
		2(S)		11		13(S)	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
21	0-10	9.4	15.3	29.1	31.0	10.8	16.4
	10-20	23.0	13.4	14.2	5.9	13.2	17.6
	20-30	27.8	30.3	8.4	12.8	6.3	6.2

[1]Site where standpipe measures were taken.
[2]Equipment breakdown.

Appendix 19. Sorting coeffecient (sc) of freeze cores divided by depth strata from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1979-1980.

		Poplar Creek				South Mills River	
Sample Week	Depth Strata	Site		Site		Site	
		7		9		15	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
8	0-10	4.3	2.6	5.2	7.1	1.6	2.4
	10-20	4.6	2.8	2.8	7.2	2.7	1.9
	20-30	1.5	1.7	1.9	--	2.0	3.1
		5		10		14	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
17	0-10	5.5	6.9	7.4	1.4	2.2	2.6
	10-20	6.5	4.8	3.3	5.0	2.8	3.9
	20-30	2.4	2.0	1.9	4.1	3.4	2.0
		2		11		13	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
21	0-10	3.3	2.1	1.6	1.5	2.6	2.3
	10-20	1.7	2.4	2.5	4.6	3.6	2.7
	20-30	1.6	2.1	2.8	1.8	5.3	3.8

Appendix 20. Fredle index (fi) of substrate in freeze cores by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980.

Sample Week	Depth Strata	Poplar Creek Site		Poplar Creek Site		South Mills River Site	
		7		9(S)[1]		15(S)	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
8	0-10	2.3	5.8	1.0	1.0	15.4	7.2
	10-20	0.6	5.7	3.5	1.0[2]	5.6	9.5
	20-30	11.0	8.0	6.9	--	10.1	3.9
		5(S)		10		14(S)	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
17	0-10	1.5	0.8	1.1	17.4	5.7	2.5
	10-20	0.8	2.4	4.4	1.3	3.3	1.2
	20-30	8.2	8.2	16.6	1.3	3.1	3.8
		2(S)		11		13(S)	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
21	0-10	2.9	6.5	18.9	20.4	4.2	7.0
	10-20	13.3	6.4	5.7	1.3	3.7	6.6
	20-30	17.8	16.6	3.0	7.3	1.2	1.6

[1]Site where standpipe measures were taken.
[2]Equipment breakdown.

Appendix 21. Percent fines ($\leq$ 2.00 mm) of substrate in freeze cores by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980.

		Poplar Creek				South Mills River	
Sample Week	Depth Strata	Site		Site		Site	
		7		9(S)[1]		15(S)	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
8	0-10	24.3	17.8	36.7	34.3	5.5	14.6
	10-20	47.3	18.2	22.2	35.0	16.7	12.2
	20-30	9.4	12.3	15.8	33.7	12.9	17.4
		5(S)		10		14(S)	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
17	0-10	16.6	22.2	30.5	29.7	16.5	22.9
	10-20	23.3	24.4	20.2	29.7	19.7	30.7
	20-30	13.3	12.0	8.3	12.4	19.9	16.3
		2(S)		11		13(S)	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
21	0-10	20.7	16.7	12.1	10.6	18.4	13.6
	10-20	9.3	14.0	17.1	30.3	14.9	13.7
	20-30	10.4	8.2	19.8	15.0	30.8	25.4

[1]Site where standpipe measures were taken.

Appendix 22. Porosity (%) of substrate in freeze cores by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980.

		Poplar Creek				South Mills River	
Sample Week	Depth Strata	Site		Site		Site	
		7		9		15	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
8	0-10	24.0	23.1	24.6	22.7	7.4	18.6
	10-20	33.1	18.5	18.6	22.4[1]	15.4	10.9
	20-30	14.6	20.8	14.9	--	10.0	16.1
		5		10		14	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
17	0-10	25.1	33.3	32.7	22.8	22.6	25.3
	10-20	28.7	24.4	17.6	22.8	25.6	30.8
	20-30	17.7	17.1	10.4	11.2	25.1	24.9
		2		11		13	
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd
21	0-10	23.8	17.6	17.3	12.4	20.8	16.0
	10-20	17.4	18.4	20.3	25.8	14.6	17.3
	20-30	20.5	12.2	19.9	20.9	23.4	29.3

[1]Equipment breakdown.

Appendix 23. Geometric mean diameter (mm) of substrate in freeze cores by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980-1981.

		Poplar Creek				South Mills River			
Sample Week	Depth Strata	Site		Site		Site		Site	
		18		22(S)[1]		24			
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd		
4	0-10	10.0	19.1	12.1	28.4	21.2	4.1		
	10-20	10.3	16.7	10.5	16.6	10.4	17.6		
	20-30	15.5	9.7	3.6	4.2	12.2	17.7		
		19(S)				5(S)		8	
		Redd	Nonredd			Redd	Nonredd	Redd	Nonredd
11	0-10	19.9	5.5			10.8	9.1	10.7	23.4
	10-20	6.9	14.4			15.8	14.7	19.6	19.2
	20-30	10.5	22.0			23.3	8.0	9.6	25.7
		13(S)				3(S)		10(S)	
		Redd	Nonredd			Redd	Nonredd	Redd	Nonredd
17	0-10	10.6	4.2			24.4	27.4	12.9	29.7
	10-20	8.4	22.6			33.3	15.4	16.5	10.3
	20-30	12.4	8.8			32.8	53.5	12.0	17.3

[1]Site where standpipes measurements were taken.

Appendix 24. Sorting coefficient (sc) of substrate in freeze cores by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980-1981.

Sample Week	Depth Strata	Poplar Creek Site		Poplar Creek Site		South Mills River Site		South Mills River Site	
		18		22(S)[1]		24			
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd		
4	0-10	1.7	2.0	2.4	1.9	2.4	5.2		
	10-20	3.4	1.6	3.9	1.7	3.2	1.9		
	20-30	1.8	4.4	6.3	5.9	2.5	2.6		
		19(S)				5(S)		8	
		Redd	Nonredd			Redd	Nonredd	Redd	Nonredd
11	0-10	2.8	4.1			2.6	3.5	2.5	2.0
	10-20	4.4	3.9			1.8	3.4	1.9	1.7
	20-30	2.5	2.6			2.0	3.5	2.9	1.6
		13(S)				3(S)		10(S)	
		Redd	Nonredd			Redd	Nonredd	Redd	Nonredd
17	0-10	3.7	4.7			2.0	1.7	2.7	1.8
	10-20	2.7	2.6			1.8	3.4	2.2	3.4
	20-30	4.1	3.7			1.6	1.2	1.8	2.5

[1]Site where standpipes measurements were taken.

Appendix 25. Fredle index (fi) of substrate in freeze cores by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980-1981.

		Poplar Creek				South Mills River			
Sample Week	Depth Strata	Site		Site		Site		Site	
		18		22(S)[1]		24			
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd		
4	0-10	6.1	9.5	5.0	15.1	8.9	0.8		
	10-20	3.3	10.5	2.7	9.6	3.2	9.4		
	20-30	8.5	2.2	0.6	0.7	5.0	7.0		
		19(S)				5(S)		8	
		Redd	Nonredd			Redd	Nonredd	Redd	Nonredd
11	0-10	7.2	1.4			4.1	2.6	4.3	11.7
	10-20	1.6	3.7			8.9	4.3	10.4	11.6
	20-30	4.3	8.6			13.0	2.3	3.4	15.8
		13(S)				3(S)		10(S)	
		Redd	Nonredd			Redd	Nonredd	Redd	Nonredd
17	0-10	2.9	0.9			12.0	16.1	6.0	16.9
	10-20	3.1	8.7			18.6	4.6	9.6	3.0
	20-30	3.0	2.4			20.1	44.2	2.9	7.0

[1]Site where standpipes measurements were taken.

Appendix 26. Percent fines (≤ 2.00 mm) of substrate in freeze cores by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980-1981.

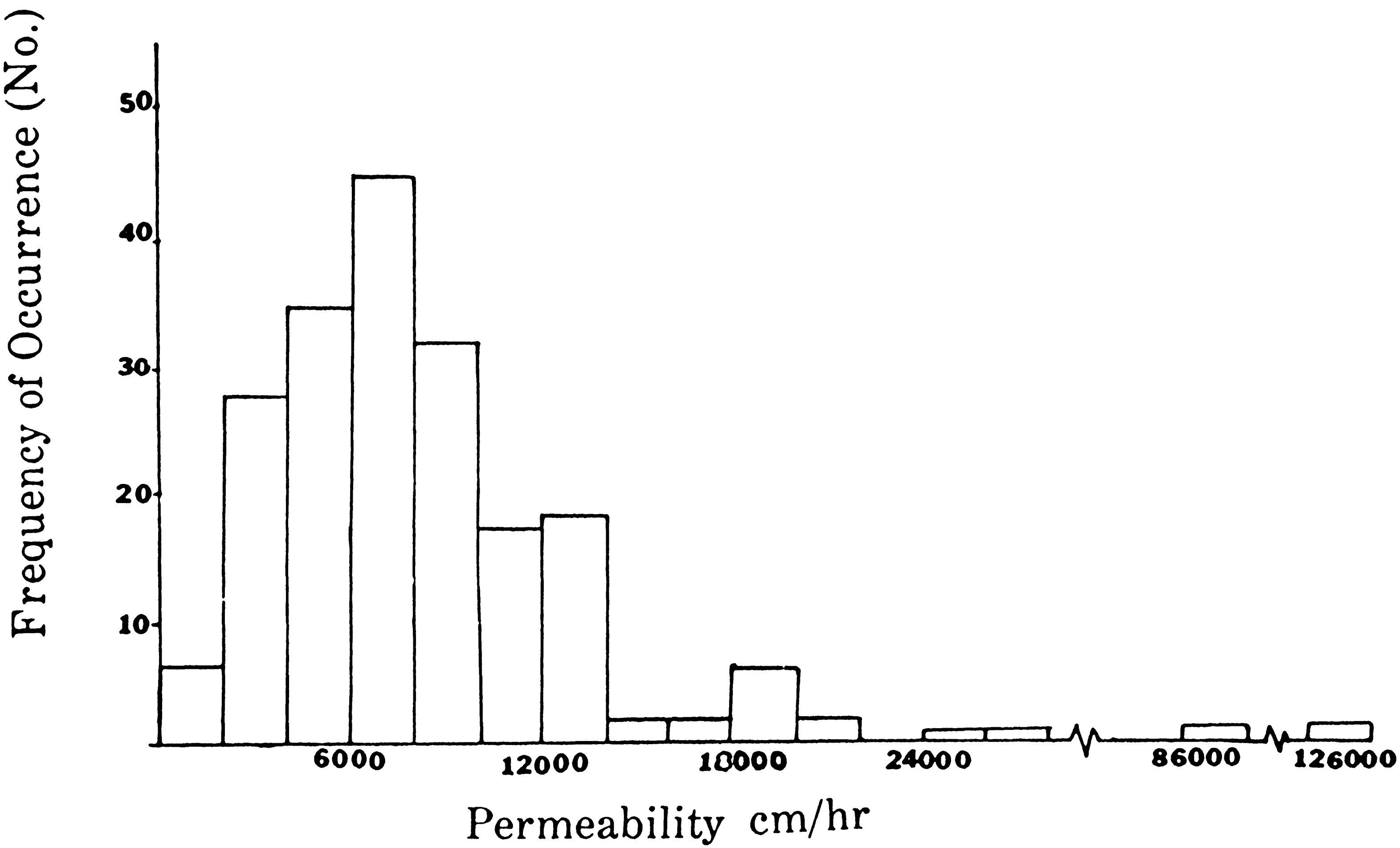
		Poplar Creek				South Mills River			
Sample Week	Depth Strata	Site		Site		Site		Site	
		18		22(S)[1]		24			
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd		
4	0-10	12.5	12.7	17.2	12.3	11.6	35.1		
	10-20	19.5	11.8	22.9	11.3	19.4	15.7		
	20-30	14.7	24.6	39.6	34.3	16.8	15.7		
		9(S)				5(S)		8	
		Redd	Nonredd			Redd	Nonredd	Redd	Nonredd
17	0-10	14.5	28.4			16.7	23.1	18.8	10.1
	10-20	31.1	20.7			13.0	18.8	15.7	12.8
	20-30	17.2	15.6			12.3	23.3	12.6	10.1
		13(S)				3(S)		10(S)	
		Redd	Nonredd			Redd	Nonredd	Redd	Nonredd
11	0-10	17.3	26.2			11.0	9.7	11.0	6.3
	10-20	32.1	22.4			8.2	17.7	13.4	22.2
	20-30	16.2	15.6			9.3	5.8	23.9	19.1

[1]Site where standpipes measurements were taken.

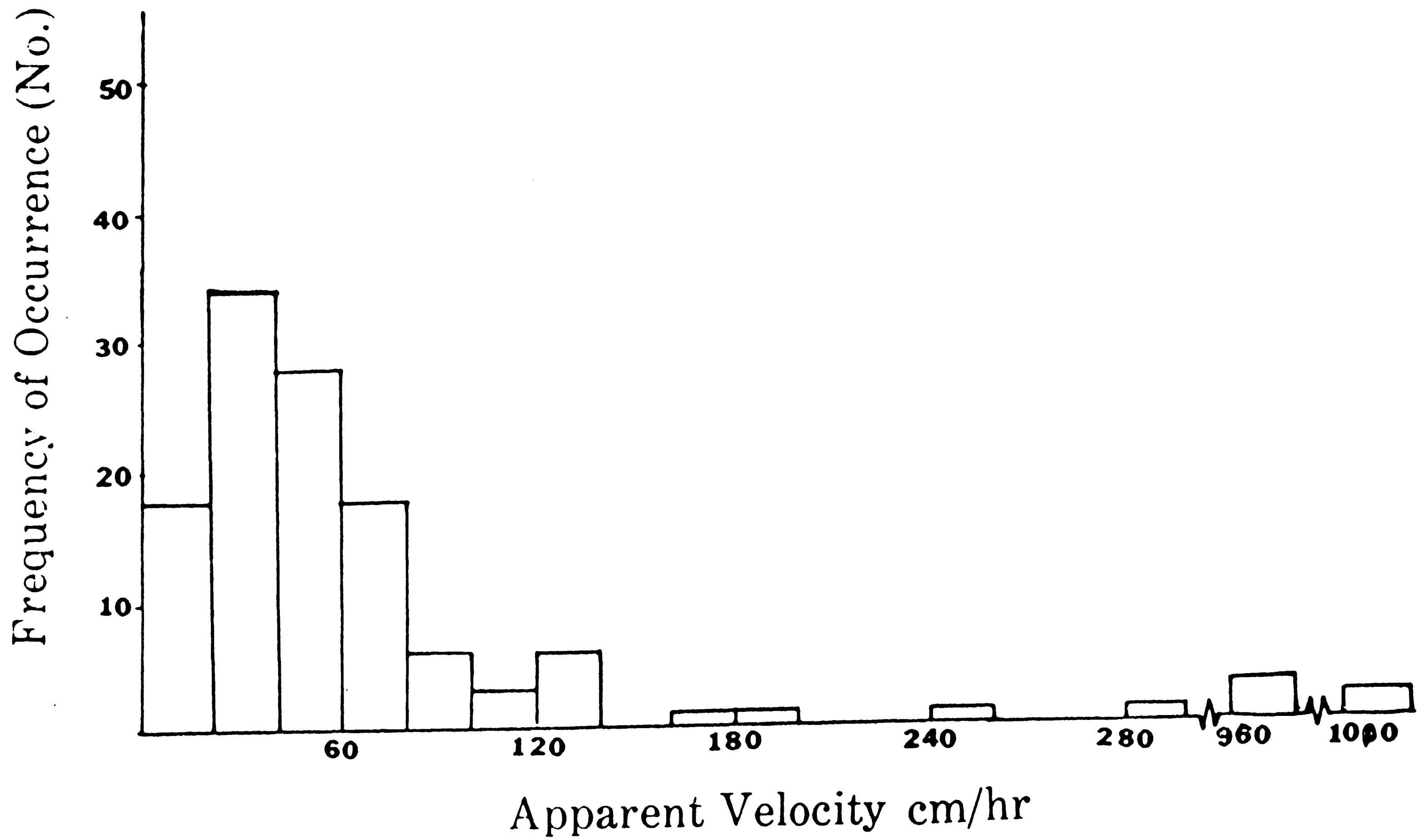
Appendix 27. Porosity(%) of substrate in freeze cores by depth strata (cm) from redd and nonredd sites on three sample dates (in weeks) on Poplar Creek and South Mills River, 1980-1981.

		Poplar Creek				South Mills River			
Sample Week	Depth Strata	Site		Site		Site		Site	
		18		22(S)[1]		24			
		Redd	Nonredd	Redd	Nonredd	Redd	Nonredd		
4	0-10	23.9	12.1	19.5	23.0	16.3	37.2		
	10-20	16.3	12.9	23.3	14.2	22.0	21.5		
	20-30	15.6	16.6	27.3	16.8	22.4	17.9		
		9(S)				5(S)		8	
		Redd	Nonredd			Redd	Nonredd	Redd	Nonredd
11	0-10	23.4	27.9			17.6	18.2	17.6	13.0
	10-20	24.8	21.6			14.3	16.2	15.9	14.0
	20-30	27.3	12.6			11.4	27.5	19.2	11.5
		13(S)				3(S)		10(S)	
		Redd	Nonredd			Redd	Nonredd	Redd	Nonredd
17	0-10	21.6	23.8			13.7	10.2	18.2	10.6
	10-20	27.1	13.5			9.1	14.4	10.2	26.1
	20-30	17.5	21.9			12.0	23.0	15.7	16.7

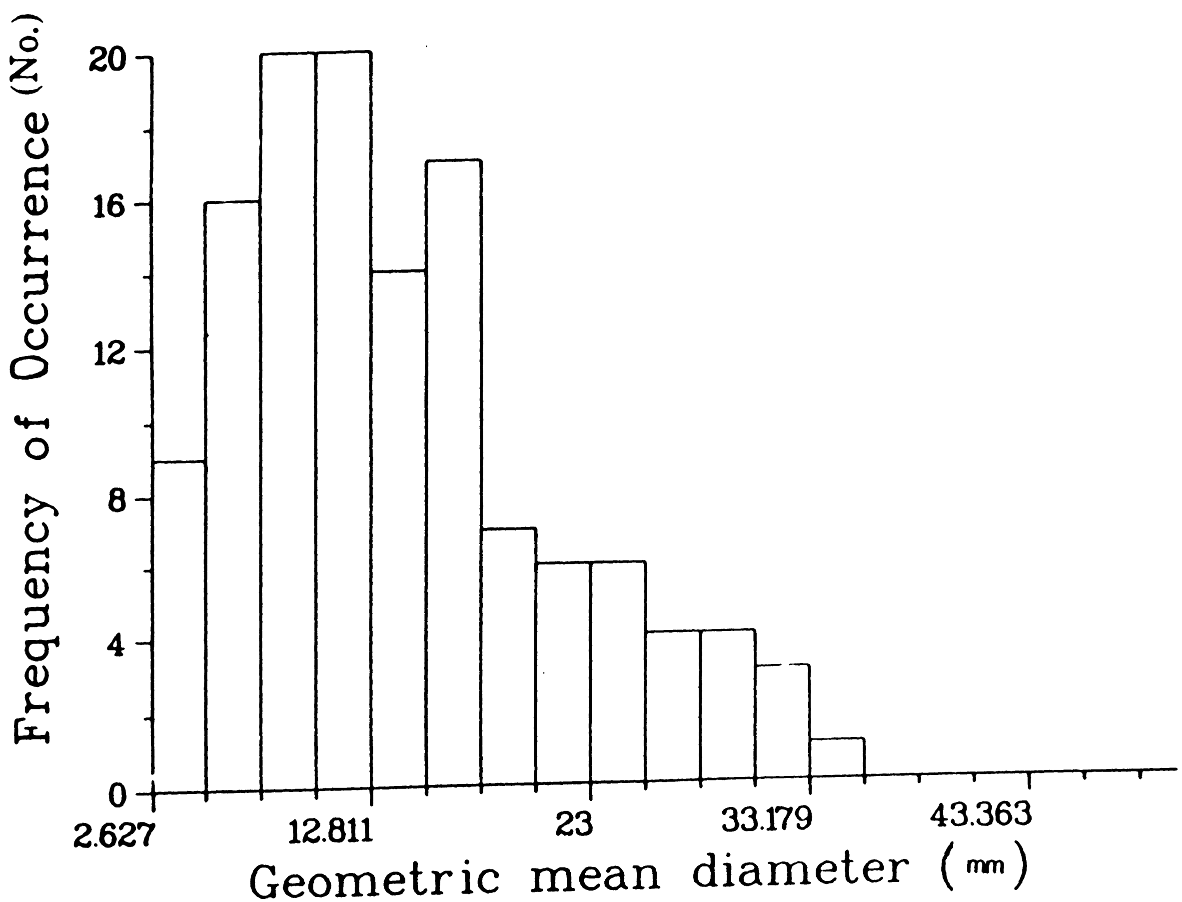
[1]Site where standpipes measurements were taken.



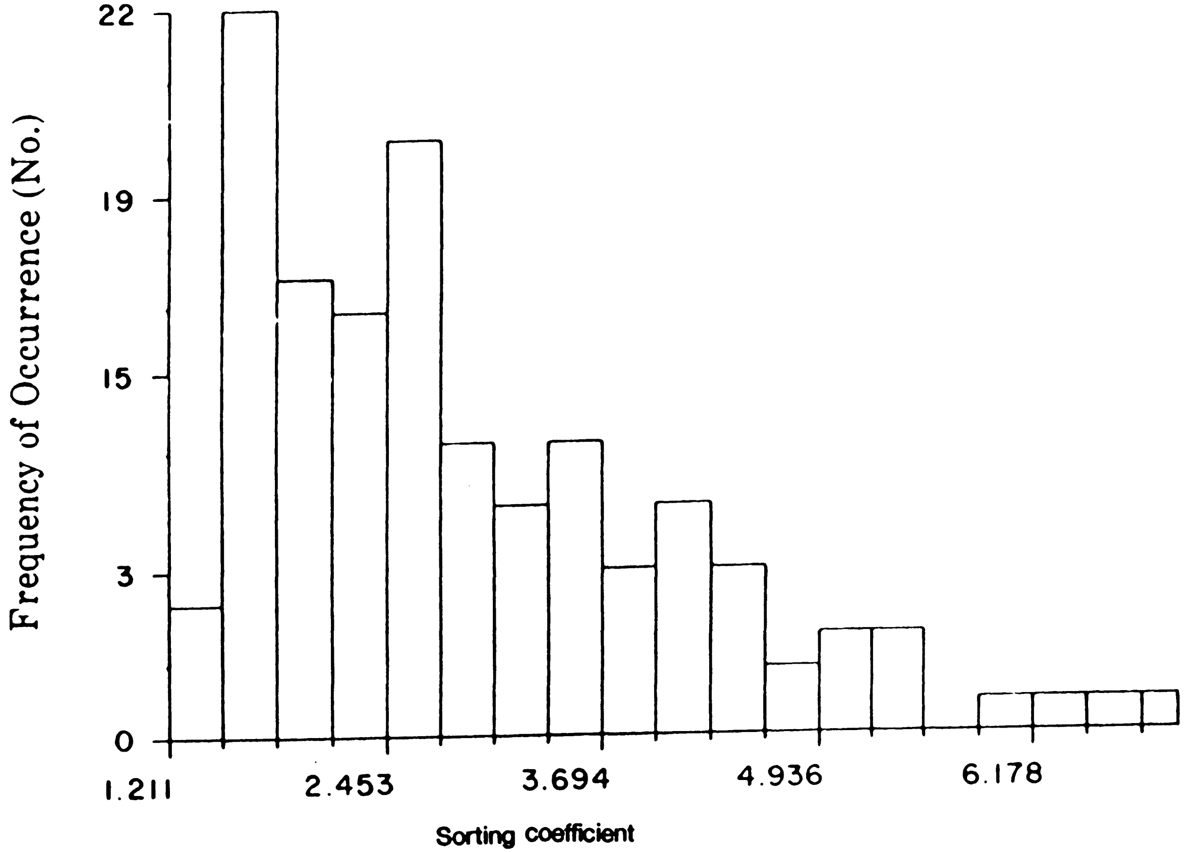
Appendix 28: Frequency distribution of permeability (K_{10}) from redd and nonredd sites, November - May 1979 - 1980 and 1980 - 1981.



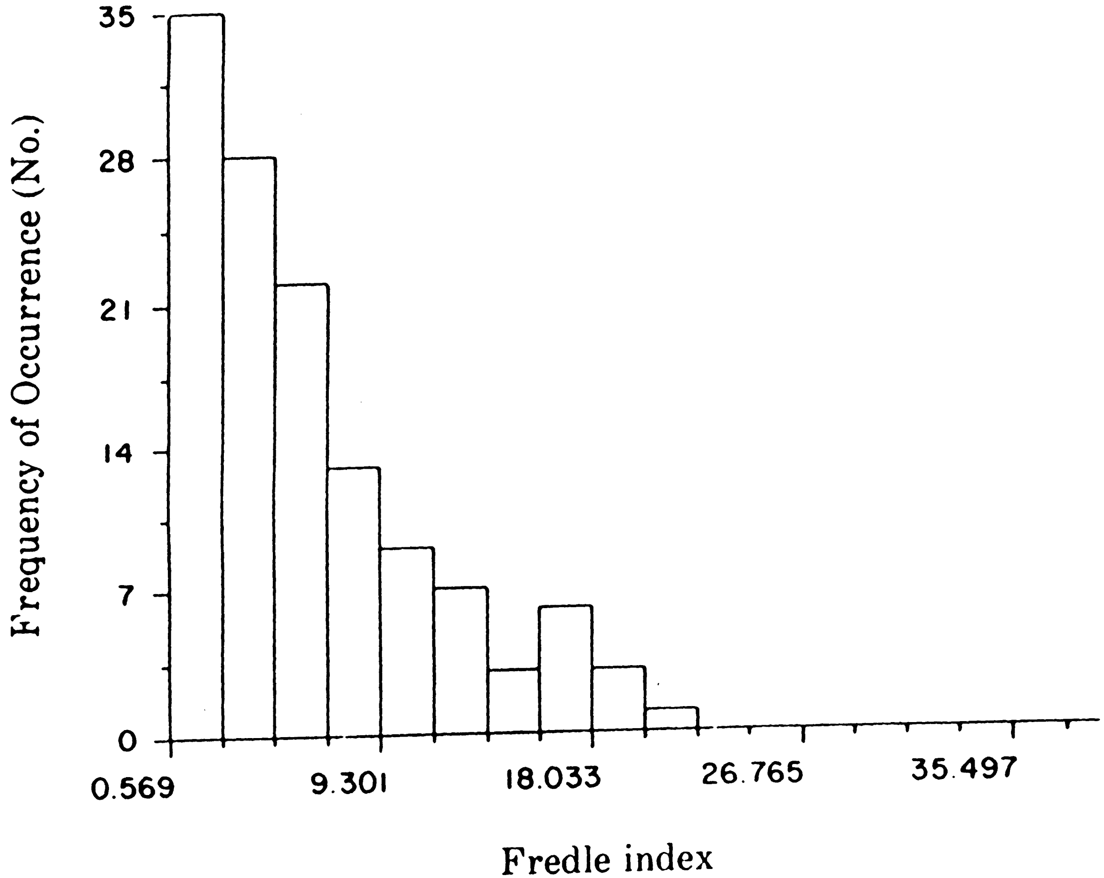
Appendix 29:Frequency distribution of apparent velocity (V) from redd and nonredd sites, November - May 1979 - 1980 and 1980 - 1981.



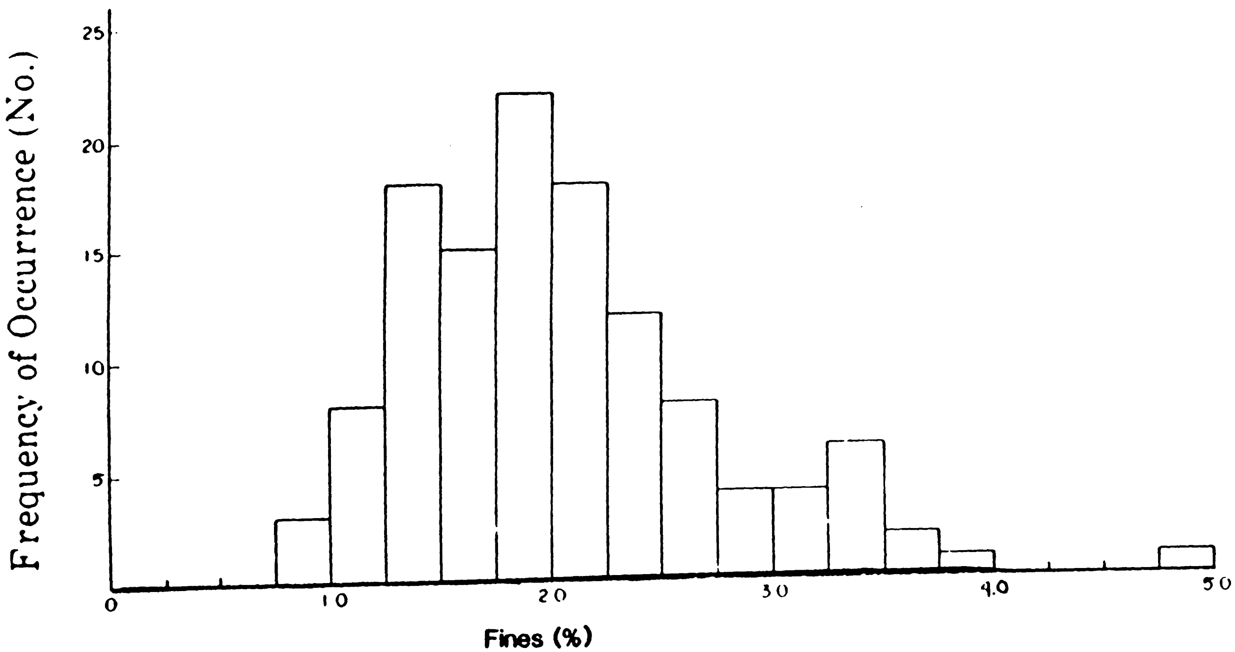
Appendix 30: Frequency distribution of geometric mean diameter from freeze cores December - March 1979 - 1980 and 1980 - 1981.



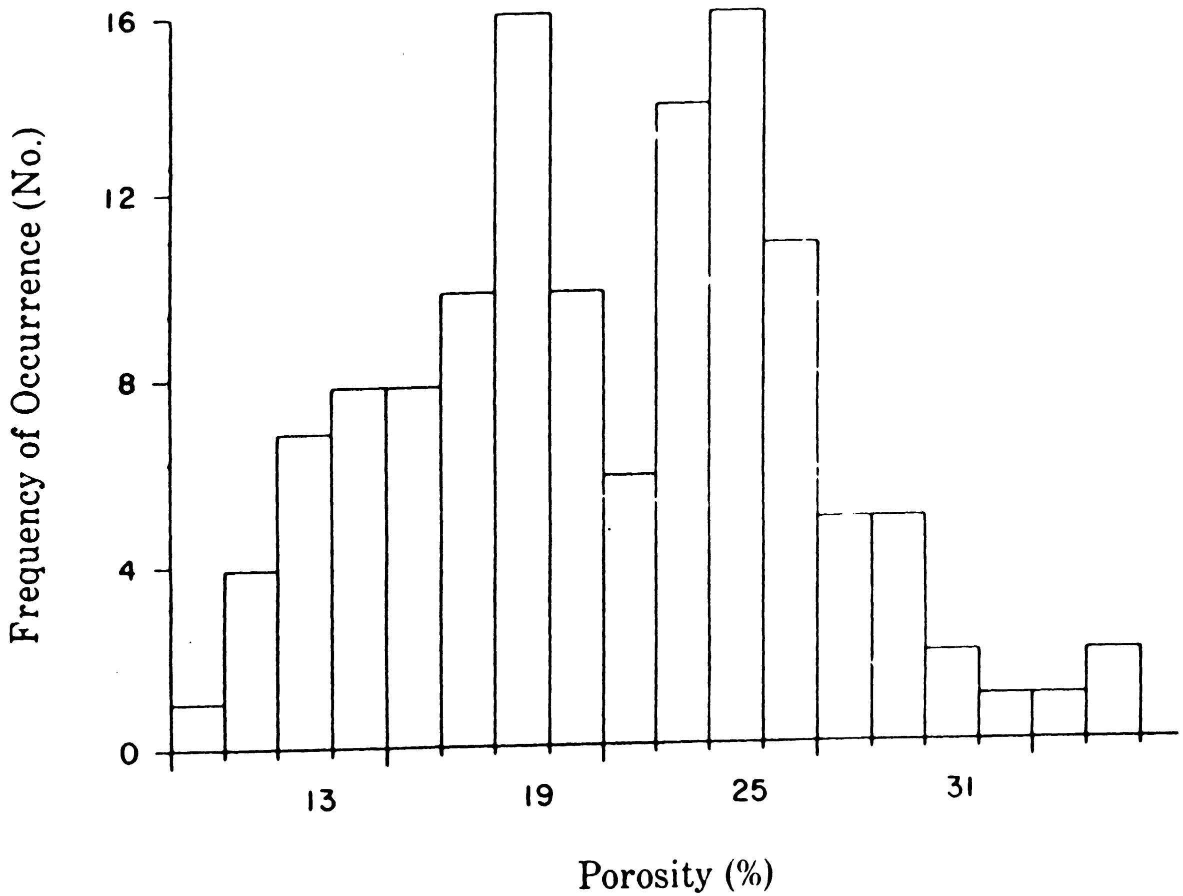
Appendix 31 : Frequency distribution of sorting coefficient (sc) from freeze cores, December - March 1979 - 1980 and 1980 - 1981.



Appendix 32: Frequency distribution of fredle index (fi) from freeze cores, December - March 1979 - 1980 and 1980 - 1981.



Appendix 33: Frequency distribution of percent fines(≤2.00 mm) from freeze cores, December –March 1979 – 1980 and 1980 – 1981



Appendix 34: Frequency distribution of porosity from freeze cores, December - March 1979 - 1980 and 1980 - 1981.

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