

Influence of groundwater flow regimes on the
distribution of minnow (Cyprinidae) spawning
nests in Tenderfoot Creek, Michigan

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ABSTRACT

A study was conducted to describe nest site preference for three species of nest-building minnows in Tenderfoot Creek, Gogebic County, Michigan. Previous studies record selection of spawning sites in areas with gravel substrate, moderate current velocity, and adequate depth to insure complete nest submersion (Vives 1990, Miller 1964). This study addresses the effects of hyporheic and groundwater flow hydrology on nest site preference. Water chemistry, dissolved oxygen concentration, and temperature measured both within the spawning cup and outside the nests indicated that flow regimes within the nest interior are interactive with the stream. Substrate temperature measurements and piezometer-well implantment located 2 sites of pure spring seepage ($T < 14^{\circ}\text{C}$) and 4 seepage-influenced sites within the channel which were avoided by nest-building minnows. In recent years investigations have recognized the substantial influences hyporheic and substrata processes have on the stream channel biota. The spawning cups of minnow nests occur at the interface of the hyporheic zone and the stream water column. Thus assessment of nest site preference must include considerations of hydrologic processes.

INTRODUCTION

Exchange of water between a stream and the underlying aquifer occurs in a complex pattern called a flow regime (Black 1991). Flow regimes are determined by the geologic and topographic features of a region and may vary among local areas of a stream (Price 1985, W. C. Price unpublished data). The chemical composition, or *signature*, of groundwater is dictated by the reactions that occur among the minerals and ions within the substrata. Consequently, the quality of water discharged to the stream varies according to the chemical nature of the subterranean source (where the groundwater is stored) and the path by which the water travels (Schafran 1988, Hill 1990, Gibert 1991). For example, Gerla (1992) correlated carbonate precipitation, dissolution of gypsum, and clay cation exchange reactions with specific substrate locales and the occurrence of three basic chemistries (HCO_3 , SO_4 , and Cl) of discharged surface waters. Chemical changes undergone by migrating groundwater within the substrata, or the geochemical evolution, has been studied primarily for water resource management and for predicting the effects of pollution (Gerla 1992, Simpkins 1992, George 1992). Investigation of the chemical effects of geochemical evolution in the stream channel and hyporheic zone has gained only recent attention (Valett et al 1993).

Located within the substrata, groundwater lacks exposure to the surface environment. Insulation from surface temperature changes constrains groundwater temperature to within a fairly limited range. In contrast the stream water column temperature fluctuates seasonally in a lag response to the weather (Hynes 1983, Stanford and Ward 1988). Using continuous time-series monitoring, Silliman (1991) reported an annual variation in temperature of only 2.8°C for groundwater discharge into an Indiana stream. Depending on the regional pattern of groundwater discharge, lateral diffusion in the substrate, and the degree of thermal mixing with the stream, the temperature of the streambed and hyporheic zone can vary longitudinally (Webster 1976, Stanford and Ward 1988, Berg and Lamberti unpublished data). The cumulative effect is the occurrence of longitudinal and vertical gradients in temperature, Ph, and chemistry at the substrate surface.

Spatial variation in the chemistry and temperature of water seepage has important implications for the distribution of flora and fauna at the discharge surface (Hynes 1983, Bernaldez 1989)

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and in the hyporheic zone (Stanford and Ward 1988). Particularly high concentrations of nitrogen, phosphorous, and dissolved organic nutrients also may be associated with groundwater discharge (Lillie and Barko 1990, Labaugh 1991). Lillie et al. (1990) determined that the higher levels of nitrogen and phosphorous found in groundwater seepage were associated with an increased biomass of the macrophyte *Myriophyllum spicatum* in those regions.

Groundwater generally is depleted of oxygen in comparison to the saturated water column of a turbulent stream and has a lower pH due to the presence of mineral cations (Dudley 1991). The abundant cations in upwelling groundwater hasten the precipitation of organic nutrients, creating a region that is particularly favorable to periphyton and invertebrates that tolerate low oxygen levels (Hynes 1983, Dudley 1991). Stanford and Ward (1993) term this increase of bioavailable solutes as *biogeochemical loading*. In core samples up to 10m deep in the substratum and 10km away from the stream channel, Stanford and Ward (1988) recorded stonefly (Plecoptera) densities that surpassed benthic populations in the main channel. Danielopol (1988) observed a strong relationships among temperature, nutrient levels, dissolved oxygen, pH, and the distribution of invertebrate taxa. Once specific relationships between invertebrate taxa and the chemistry of groundwater discharge are defined, it may be possible to use species distributions as indicator of groundwater pollution (Hynes 1983, Gibert 1991).

Oxygen concentration and pH are especially important to the physiological development of embryonic fish. The majority of the investigations of groundwater influence on the spatial distribution of spawning nests have dealt with the redds of salmonid fishes (Webster and Eirksdottir 1976, Sowden and Power 1985, Gunn 1986, Snucins et al. 1991). In some temperate systems where salmonids spawn, groundwater pH, and temperature serve to buffer the acidic and thermally variable conditions of snowmelt (Rekolainen 1989). Consequently, salmonids tend to construct their redds in areas of upwelling groundwater where the developing embryos will be protected (Webster and Eirksdotter 1976, Snucins 1991). Few studies have investigated the nest distributions of other lotic species in relation to substratal flow regimes. Tolerance of chemical fluctuation by embryos of the catadromous salmonids is likely to be different from the tolerance for embryos of strictly freshwater species. Tenderfoot Creek, on the northern peninsula of Michigan, supports several nest-building minnow species of the family Cyprinidae: hornyhead chubs (*Nocomis*

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biguttatus), common shiners (*Luxilus cornutus*), and creek chubs (*Semotilus atromaculatus*). In Tenderfoot Creek, the nests of these minnows are approximately 50 cm in diameter and are aggregated in preferred spawning habitat areas. Vives (1990) characterized the reproductive behavior and nest building strategy of *Nocomis biguttatus* in nearby Allequash Creek, Wisconsin, and speculated that nests were constructed to maximize oxygen circulation around the developing embryos. Unlike the salmonids, the cyprinids of Tenderfoot Creek are early summer spawners and consequently embryos are not exposed to pH fluctuations due to spring snowmelt (Vives 1990). In Tenderfoot Creek, aggregations of nests have been observed in the upstream portion of riffles, which are commonly downwelling areas during baseflow conditions (Lamberti and Berg, pers. comm.).

This study was designed to determine the relationship between the distribution of cyprinid spawning nests and the occurrence of active flow zones in Tenderfoot Creek. Temperature, pH, and chemical characteristics of upwelling regions of Tenderfoot Creek are also described. In order to assess the influence of thermal and chemical characteristics on biological parameters, the patterns of hyporheic and groundwater flow must first be described.

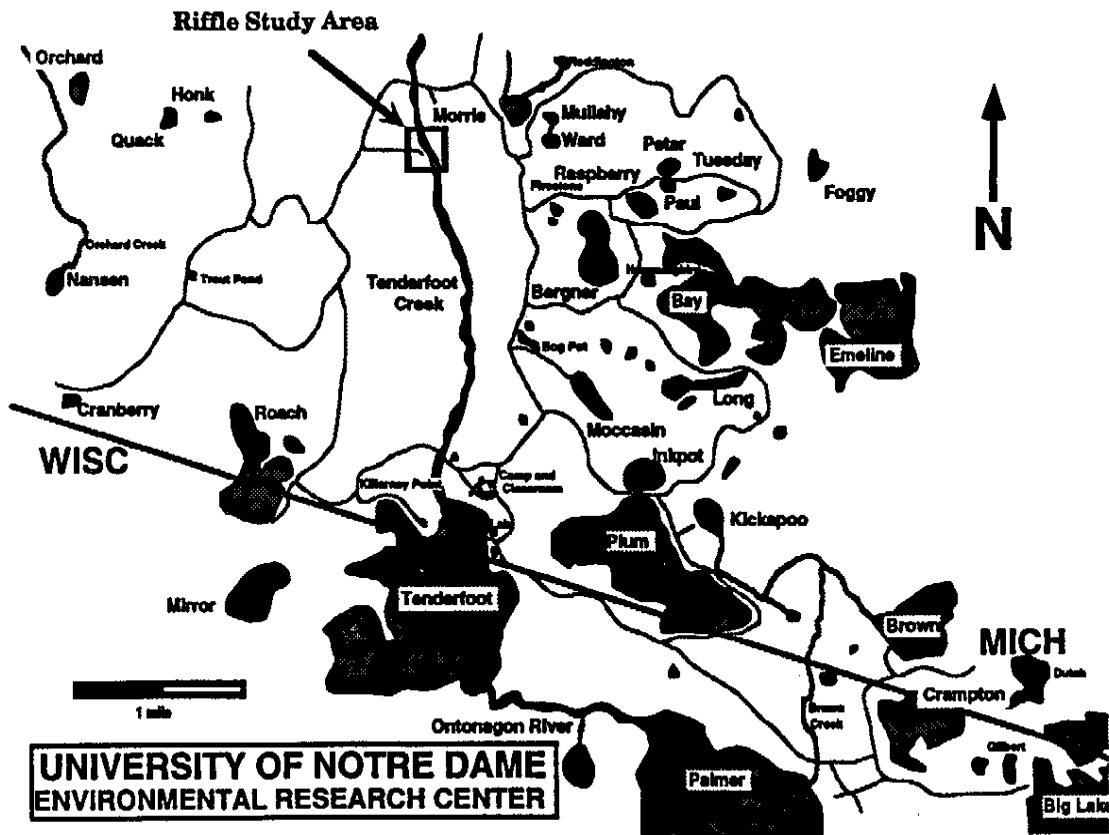
The latter task exposes the difficulty in this and other hyporheic studies. Determination of groundwater influence is confounded by the complexity of stream hydrology. Origins of a water molecule at any spatial location within the stream and the approaches appropriate for hydrological assessment vary with the geomorphology of each stream system (Bencala 1993). By searching for chemical and thermal signatures of spring seepage within the nest spawning cup this study attempted to determine whether spawning nest placement was influenced by these chemical and thermal effects.

STUDY AREA

The study was conducted in Tenderfoot Creek, Gogebic County Michigan, on Michigan's upper peninsula. The study riffle was located within The University of Notre Dame Environmental Research Center (UNDERC), approximately 3.2km downstream from where it drains Tenderfoot Lake (Fig.1). The overall gradient for this portion of the stream is 0.04% (0.4m/km), dropping from an elevation of 503m at Tenderfoot Lake to 501.5m, 0.6km downstream from the study riffle. Consequently, the majority of Tenderfoot Creek is slow moving, and in areas upstream and downstream of the

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Figure 1
Study Area



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study riffle current is virtually negligible.

The geological and glacial features of the immediate area explain the low gradient of the Tenderfoot Creek drainage basin. Although no wells have been drilled within the UNDERC property, borings on the perimeter indicate that the area is underlain by a thick glacial drift left by the most recent Alderan and Woodfordian Glacial retreats (Martin 1952, Paull and Paull 1977). Local borings, approximately 3km from the stream, reveal a drift thickness >29m overlying igneous/shale bedrock (Allen 1974). Meltwater glacial streams were likely the formative force shaping the watershed after glacial retreat (Paull and Paull 1977). Due to the poorly developed drainage system, low gradient, and depth of the confining bedrock strata, the overlying, porous glacial till is saturated. As a result the UNDERC property has numerous lakes and vernal ponds. At the riffle sights, higher gradient would result in seepage of water from the elevated saturated zone to the bank stream channel.

The streambed of most of Tenderfoot Creek is impacted with fine sediment dominated in the summer by dense macrophyte beds. The two riffle reaches within UNDERC are the only areas with measurable flow. Higher current velocity in the study riffle (summer avg.= 1.9m/s) erodes fine sediments allowing for coarser substrate composition (Berg and Lamberti, unpublished data). Substrate is perhaps the strongest determinant of Cyprinid spawning area selection (1990 Vives). The gravel/cobble substrate of the study riffle provides suitable spawning materials for minnows.

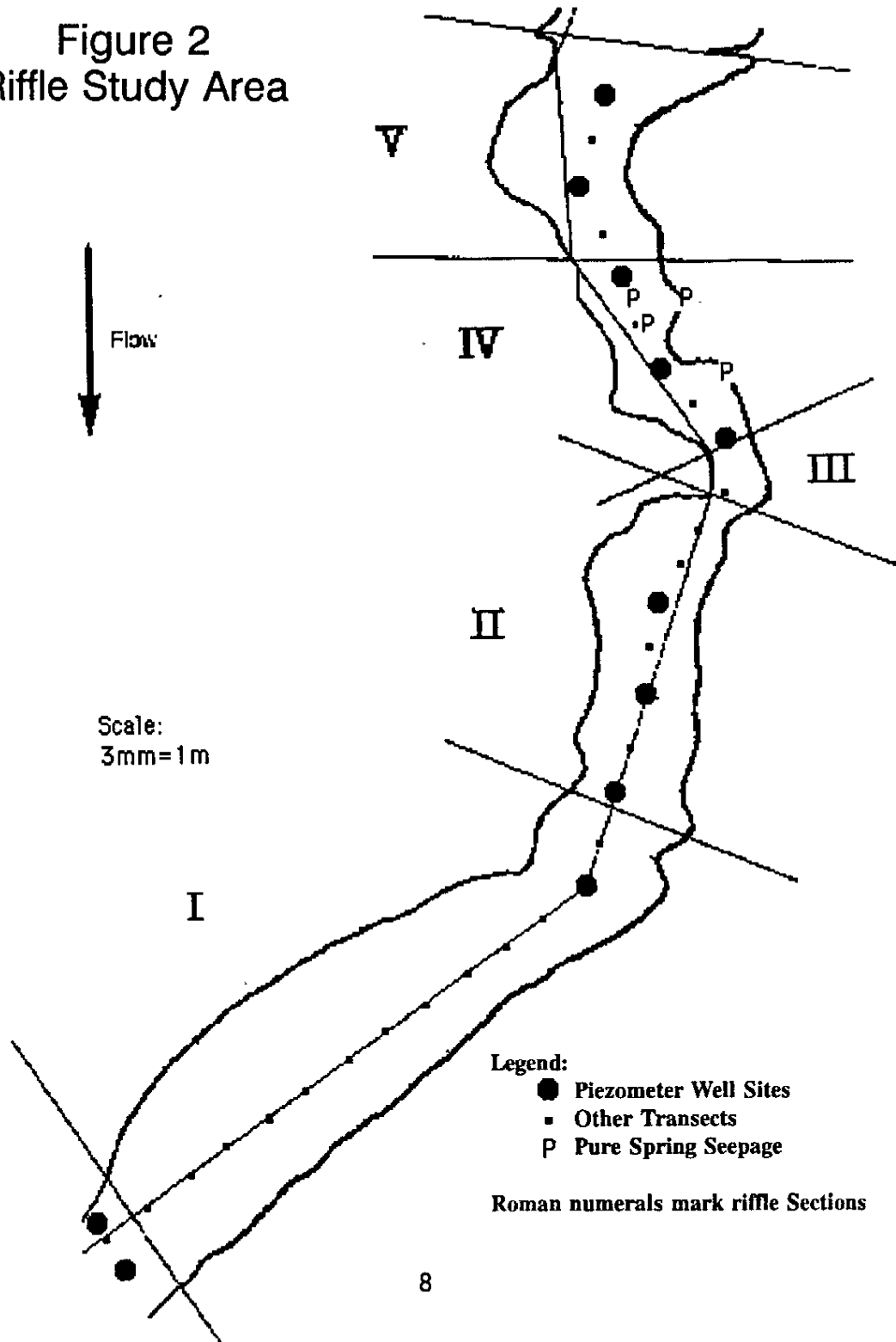
MATERIALS AND METHODS

Temperature Profile Procedures

To determine the temperature profile of the entire riffle, a grid system was imposed relative to a modified thalweg length of the stream channel (Fig.2). Transects were established every 5m with the 0m mark at the head of the riffle. Five points were designated on the perpendicular transects: 0.5m from the left bank, the center of the channel, 0.5m from the right bank, and at two points measured halfway between both banks and the center. A total of 30 transects was measured. At each point of the transect, the substrate temperature was measured by inserting the probe of a quartz thermistor (Fisher Scientific "Digi-thermo") into the substrate. The 8.9cm probe of the thermistor allowed adequate penetration of the substrate for characterizing shallow

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Figure 2
Riffle Study Area



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hyporheic temperature regimes. In addition, the water column temperature was recorded at each point and compared with substrate temperature. Differences between the two measurements were treated as the "substrate temperature depression."

Piezometer Well

Twelve piezometer wells were implanted in the substrate to more accurately characterize flow regimes. Wells were constructed of 7.5cm diameter PVC piping, trimmed to 1.5m lengths. They were driven midchannel to a depth of >0.45m at the 0, 10, 20, 30, 40, 60, 70, 80, 90, and 150m marks, and at a bank-side spring site (Fig.2). (The piezometer well at the 0m mark was immediately removed by a beaver.) Water heights in the wells were measured relative to stream water level using a Micronta Resistance Meter apparatus (S. Wondzell, Oregon State University, pers. comm.) Hydraulic-head measurements were eventually discontinued.

Nest Temperature

The spawning cup temperature of 126 nests was measured by inserting the probe of a thermistor directly into the nest mound. Location of the spawning cup within the nest was visually estimated based on earlier disassembly of several nests. Temperatures of water immediately upstream of the nest also were recorded. The majority of the active nests in the riffle were sampled, except for a few nests that occurred in clusters and thus were adjacent to sampled nests.

Dissolved Oxygen

An oxygen meter (YSI Model 23) was used to measure temperature and dissolved oxygen levels. Measurements were made for 9 well sites by evacuating the wells with a hand vacuum pump and then lowering a probe into the well during equilibration. DO levels in the spawning cup of 8 nests were measured by inserting the probe directly into the spawning cup. Stream DO was measured at 20 sites spaced longitudinally within the channel.

Nest Water Chemistry

Water for chemical analysis was extracted from the spawning cup using a pipet-tipped vacuum hose. Location of the pipet tip within the nest for water withdrawal was estimated. Occasional withdrawal of minnow eggs from the spawning cup verified accuracy of estimations. A sufficient volume (approximately 100ml) was withdrawn to conduct chemical assays (using a Hach Kit) for N-NO₃,

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N-NH₃, P-PO₄, and Ph. The methodology was the same for nest (n=22), spring (n=4), and stream (n=4) water analysis.

RESULTS

Temperature Profile

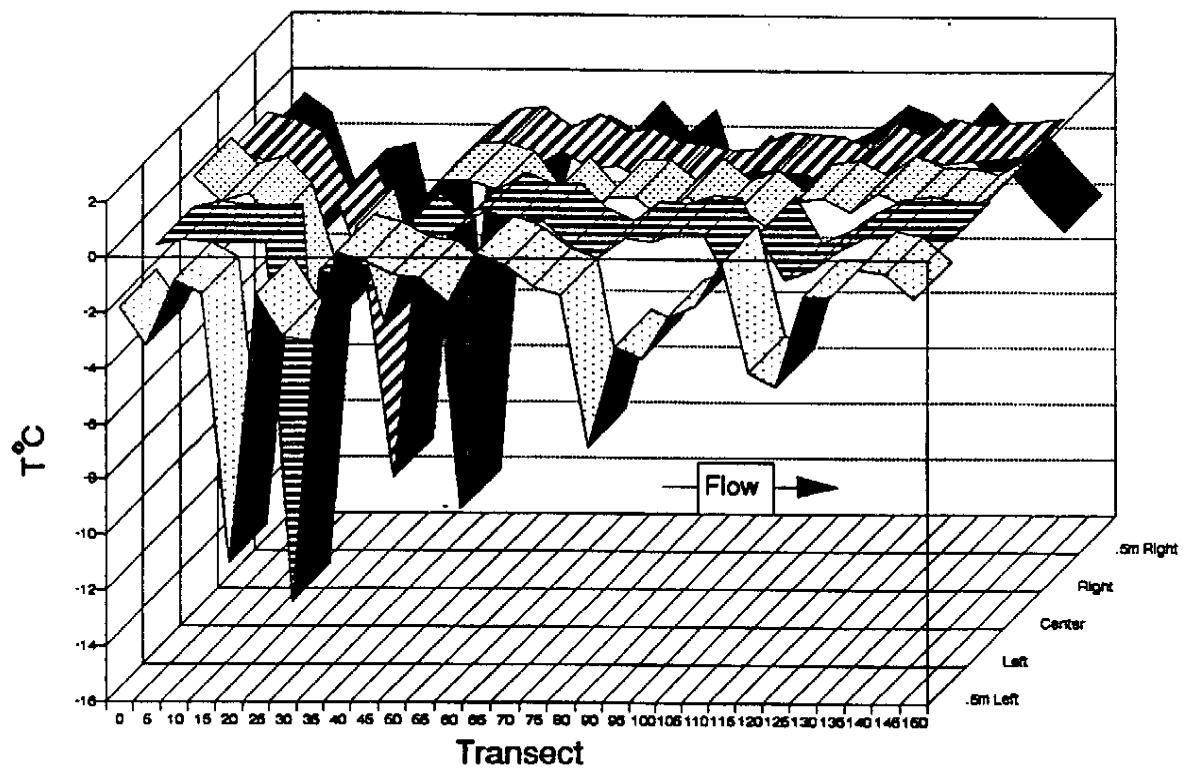
The profile of substrate temperature for the entire riffle indicated a low incidence of thermal influence of the channel substrate by groundwater upwelling. At most sites stream temperature was slightly higher than substrate temperature (Fig.3). Major substrate temperature (>8°C) depressions occurred on four transects: at 20, 25, 30, and 35m (Fig.3). These point temperature depressions are reflected in the averaged temperature depressions across the four transects: 4.28°C, 6.46°C, 4.36°C, and 5.32°C (Fig.4). These values were substantially above the mean depressions for the other transects, (\bar{x} =1.29°C). Only one of these colder sites, (13.8 °C at 0.5 right, 30m) resembles the thermal signature of pure spring seepage recorded at the bank-side springs (8°C and 10°C). Two strong spring seepages occurred at bank sites along the channel. The substantial volume of water seeping from these sites tended to flow down the right side (facing upstream) of the stream, giving false indications of spring seepages at immediately downstream areas. Right bankside areas of riffle section "I" were cooler, showing evidence of minor effluent seepage. However, groundwater influence within the wetted channel was not detected in section I.

Piezometer Results

The hydraulic pressure within the substrate, determined by piezometer implantment, were neutral to positive. No negative pressures were observed (Fig.5). Piezometers were placed at the center point of the transects established in the temperature profile, and thus were expected to reflect the thermal determinations of spring seepage at those sites. Hydraulic head heights were not closely correlated ($r=.255$, $p=.477$) with the point-specific substrate temperature depressions recorded with the thermistor at the same sites. Statistical reliability of the piezometer-well measurements could not be determined with the experimental design because well-implants could not be replicated. Equilibration of piezometer water levels was not consistent at later dates.

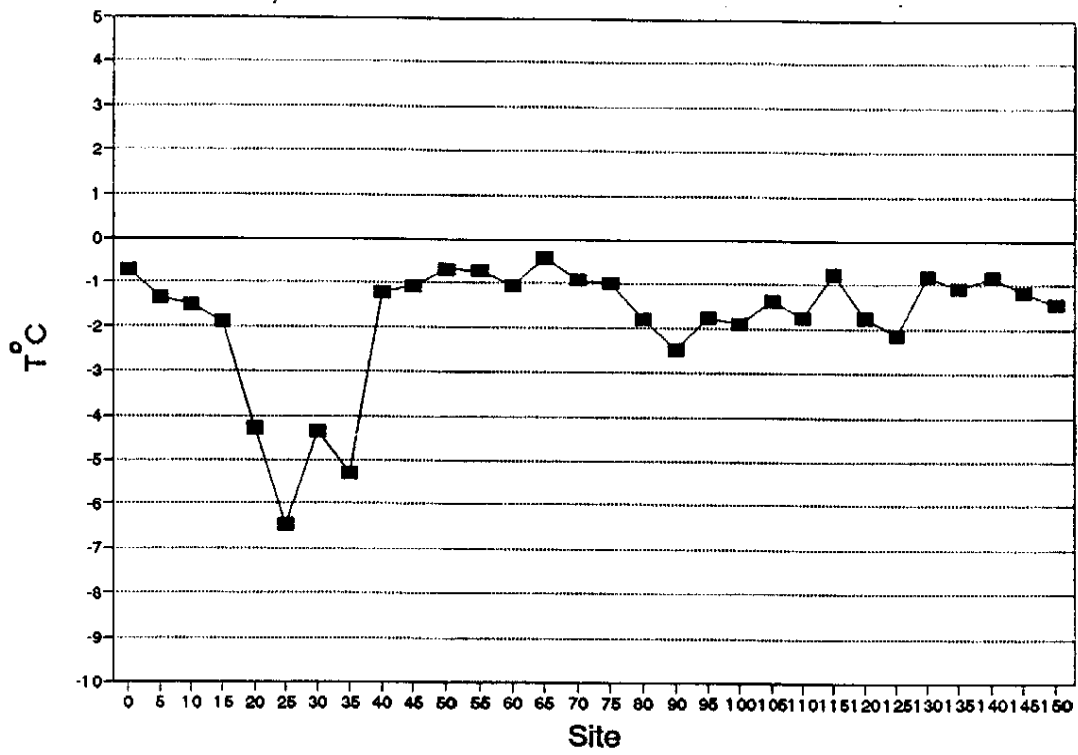
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Figure 3
Substrate Temperature Depression



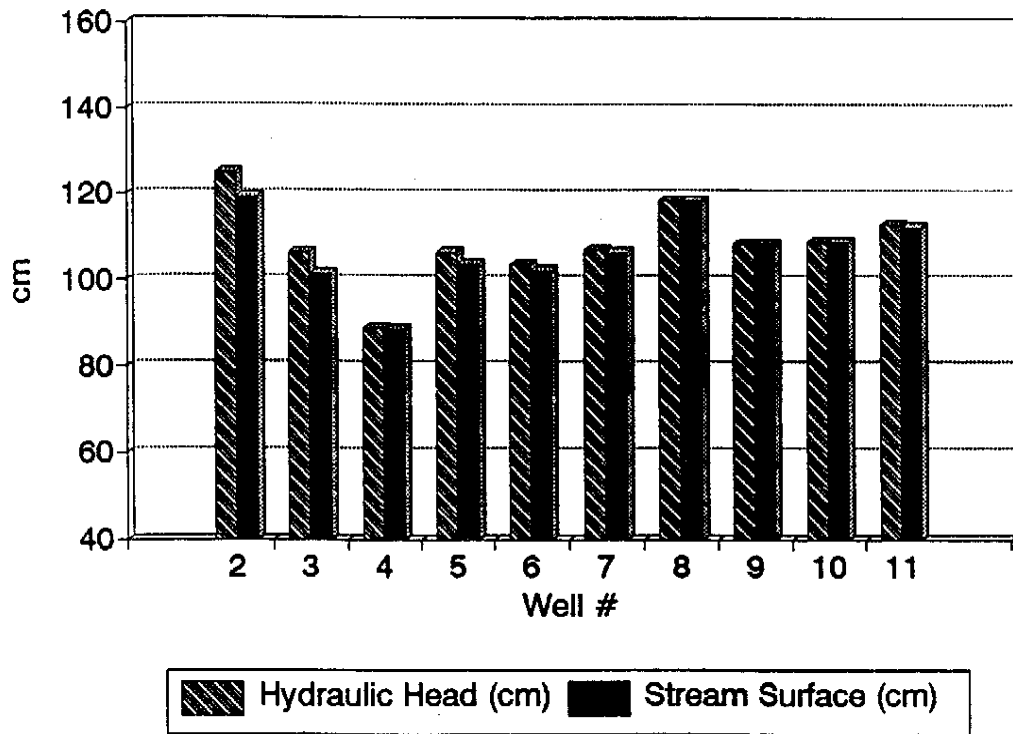
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Figure 4
Avg. Substrate Temperature Depression



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Figure 5
Piezometer Well-Heads



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Nest Temperature

The spawning cup temperatures were consistently within 3°C of the immediately surrounding stream temperature (Fig.6). Paired T-tests (Systat version 5.02) were used to separately compare stream temperature with spawning cup temperature (n=126) and stream temperature with spring temperature (n=4). The mean temperature difference between the spawning cup and the stream was small ($\bar{x}=-0.6$) but significantly different from zero ($t=-4.69$, $df=125$, $p<.001$). The difference between spring and stream temperature was much greater ($\bar{x}=15.625$, $t=45.623$, $df=3$, $p<.001$).

Dissolved Oxygen

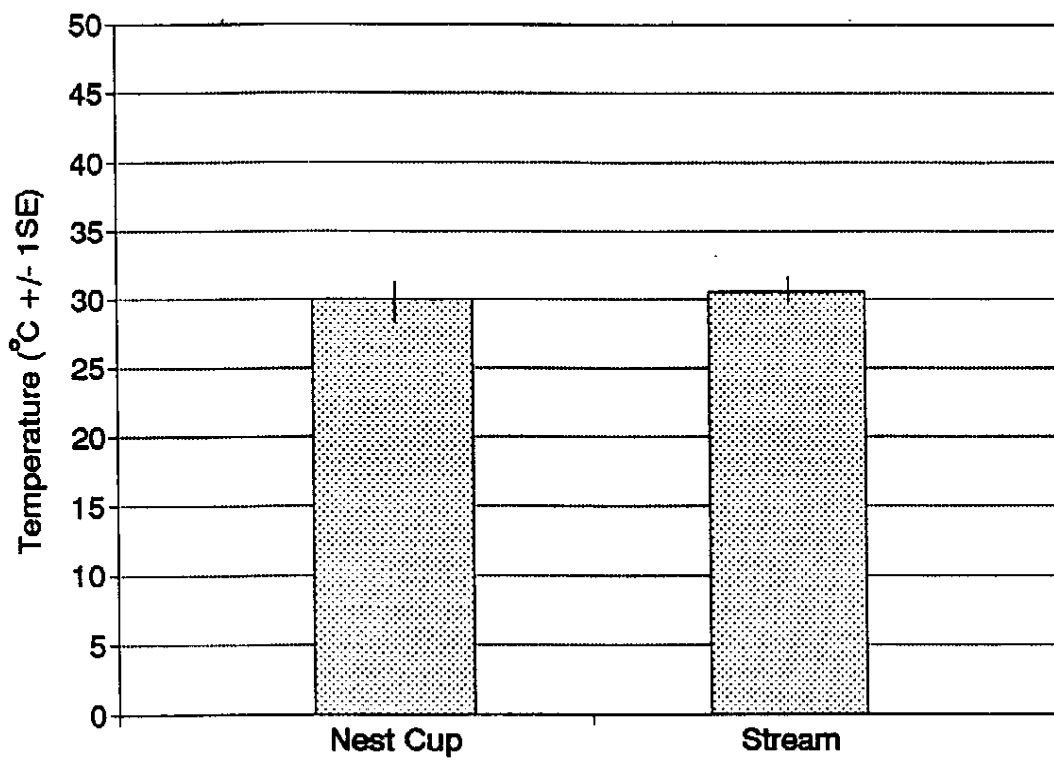
Comparison of the dissolved oxygen concentration in the springs, nests, and stream yielded conclusive differences (Fig.7). Mean spring DO concentrations was approximately half the DO concentration within the spawning cup and in the surrounding water column. ANOVA was used to compare stream DO (n=12), nest DO (n=8), and spring DO (n=4). Differences in dissolved oxygen concentration were significant among the three sites ($F=243.7$, $df=2,21$, $p<.001$). Tukey Post-Hoc analysis demonstrated significant differences between nest, springs, and stream DO levels. DO concentration was also measured at each pure spring with a corresponding stream DO measurement for that specific location. A Paired t-test was used to analyze the difference between spring DO (n=4) and local stream DO (n=4) at the stream sites. The mean difference in dissolved oxygen concentration ($\bar{x}=0.4$) was significantly different ($t=8.7$, $df=7$, $p<.001$).

Nest Water Chemistry

Orthophosphate, Nitrate-nitrogen, and Ph levels fluctuated within the same range for all sites (Figs. 8, 9, and 10). Means for stream and spring ammonia concentration were similar, but the mean ammonia concentration for the nest samples ($\bar{x}=0.284\text{mg/L}$) was nearly two times higher than both the stream ($\bar{x}=0.160\text{mg/L}$) and the spring concentration ($\bar{x}=0.138\text{mg/L}$) (Fig. 11). Bartlett distributional analysis indicated that none of the four chemical parameters were distributed normally. Data transformations were applied to satisfy the assumptions of ANOVA. Ammonia concentration, to which square-root transformations were applied, was the only parameter which differed significantly among the three sites ($F=3.851$, $df=2,15$, $p=.045$). However Tukey Post-hoc analysis did not detect significant difference between any two of the sites.

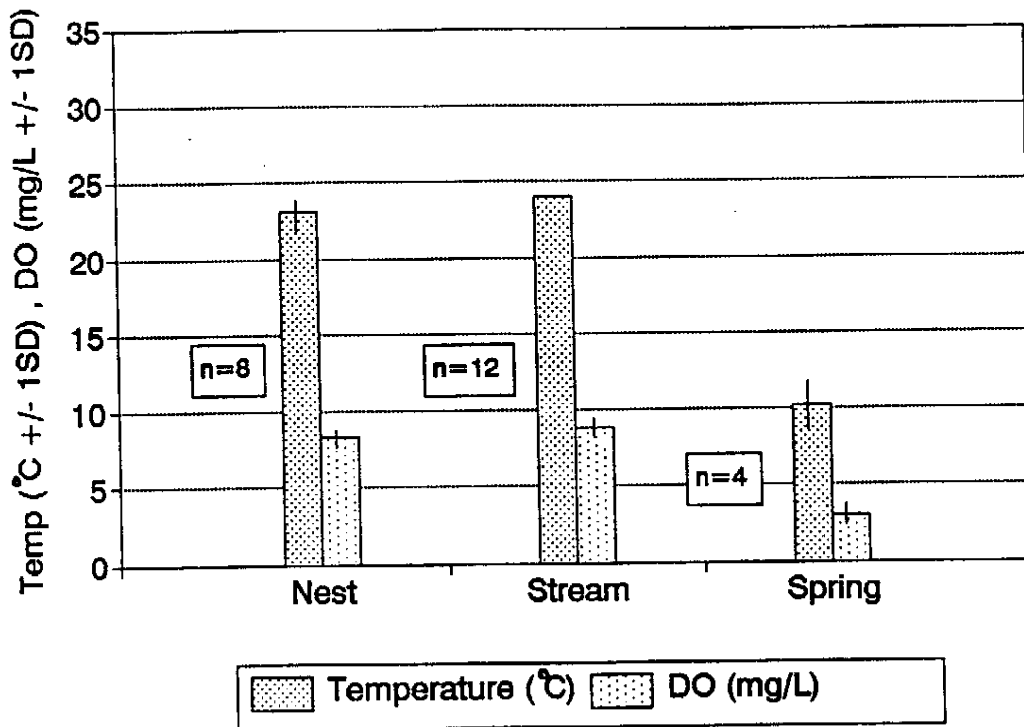
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Figure 6
Nest versus Stream Temperature



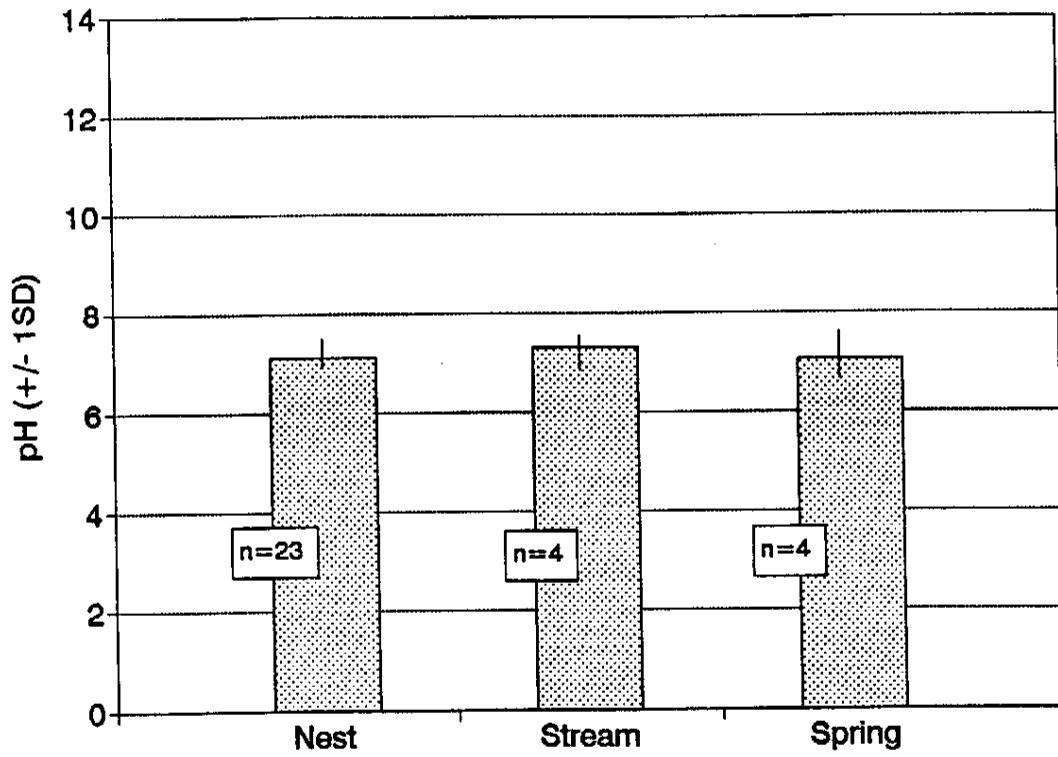
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Figure 7
Temperature and Dissolved Oxygen



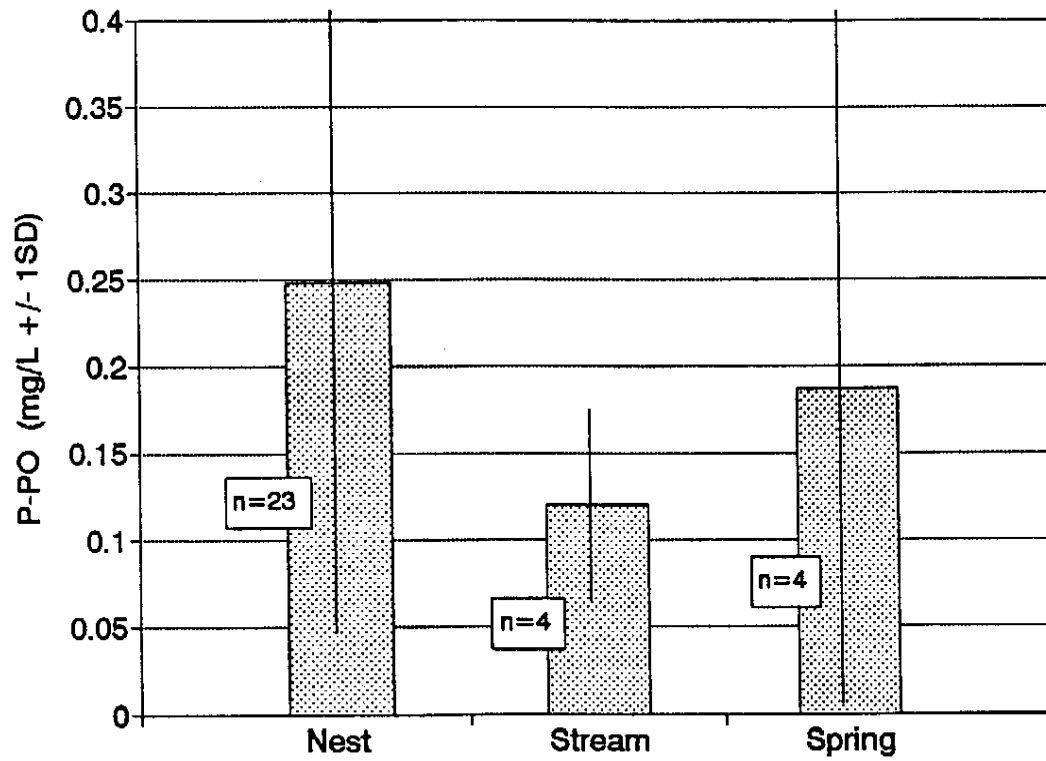
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Figure 8
pH



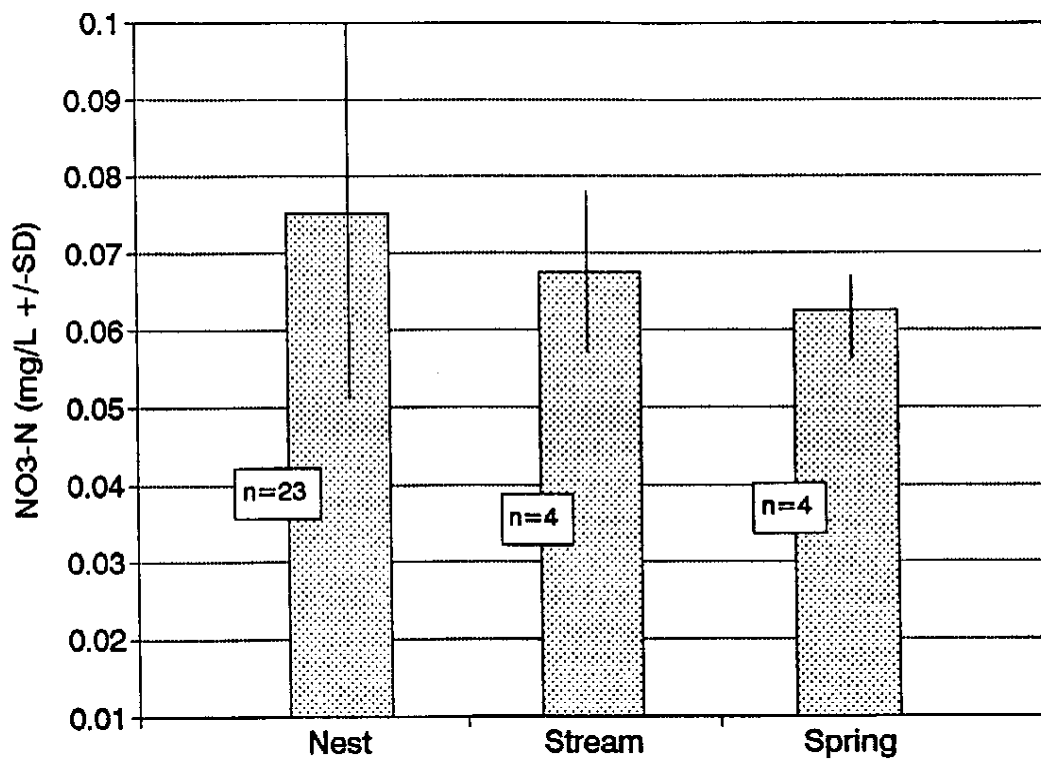
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Figure 9
Orthophosphate



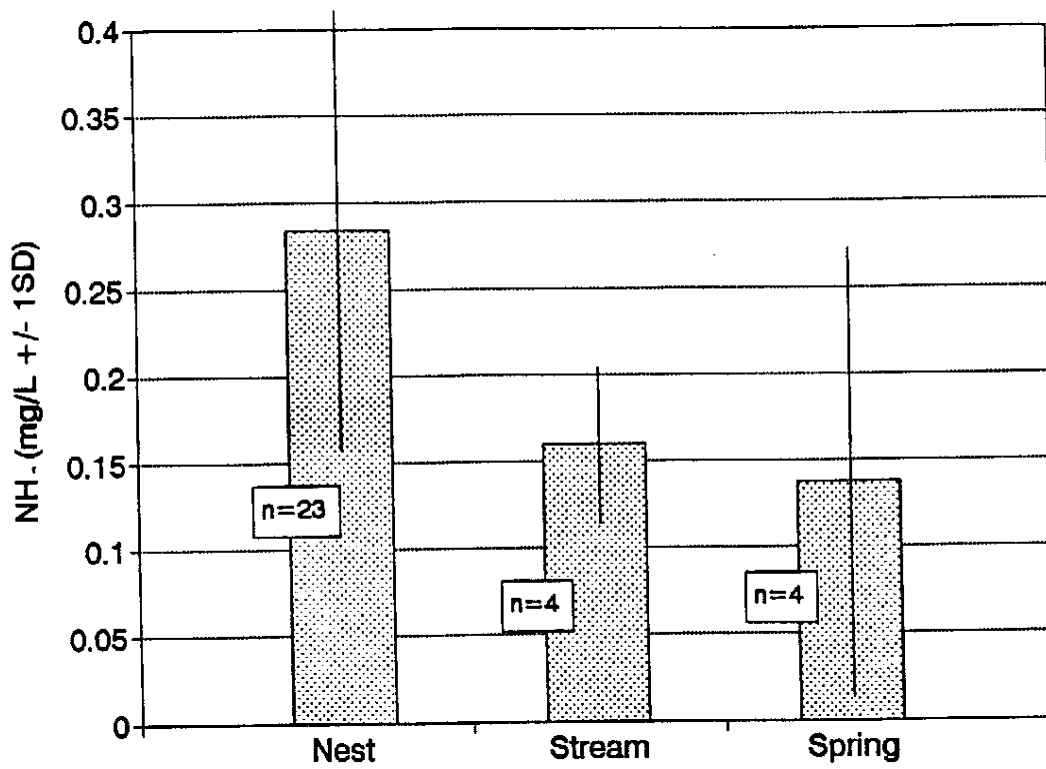
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Figure 10
Nitrate - nitrogen



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Figure 11
Ammonia



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DISCUSSION

I. Temperature Profile

Total area of stream substrate influenced by upwelling was considerably less than expected. The change in gradient which occurs at riffles typically results in abundant bank and midchannel seepage through the permeable riffle substrate. The temperature profile indicated groundwater seepage in many bank areas but little upwelling within the wetted channel (Fig.2). The areas of groundwater influence within the wetted channel were exclusively located in the upstream portions of the riffle (sections IV and V, Fig.2). Bank seepage areas were typically anoxic with silt or mud substrate. Low temperature and dissolved oxygen concentration of groundwater is likely to create these conditions.

Piezometer

Hydraulic-heads were slightly elevated indicating positive pressure within the substrate (Fig.5). Positive hydraulic-head was expected, however the temperature profile (which is certainly more reliable) does not verify strong seepage at the specific well sites. Piezometers were located midchannel, at sites where temperature measurements did not detect groundwater thermal signature.

In contrast neutral hydraulic head was recorded in much of the upstream portion of Tenderfoot Creek. The glacial drift geology indicates that the stream is unlikely to be confined by impermeable substrata. Thus hydraulic head neutrality in these low gradient areas was interpreted to indicate equilibrium of the stream with the saturated zone. In this section the stream is sluggish allowing for macrophyte growth, and substantial detrital and fine sediment deposition.

Piezometer well monitoring proved difficult because subsequent piezometer equilibration was complicated by impaction of silt in the lower outlets.

Nest temperature

The similarity of nest temperature to water column temperature strongly supported the hypothesis that spawning nests are located at sites exclusively influenced by stream water. Significant differences were observed between the water column and the nest. This difference is likely due to a temporal lag in temperature within the nest during diurnal temperature

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fluctuations. Nest temperature measurements were made at different times of the day, consequently, the sign of the lag reversed as the stream began to cool. Previous descriptions of minnow nest construction do not attempt to characterize these diurnal temperature fluctuations within the spawning cup. Additionally, the cycle of water renewal in the nest may vary depending on current velocity, depth, and position of each nest. Detecting a relationship to characterize the lag pattern is complicated by these two factors.

Previous studies have shown that unseasonal temperature declines during spawning periods can slow nest-building and mating activity appreciably (Miller 1964). All three species of the studied cyprinids have limited temperature ranges in which they will spawn (Becker 1983, Miller 1964). However the effect of the same magnitude of temperature drop between the different species and even between populations of the same species can vary widely (Miller 1964). Miller (1964) noted that spawning activity would halt completely at 22°C for one population of *Nocomis biguttatus*, while another local population would continue spawning at 14°C. The physiological and psychological processes governing these intra-and inter-species variations have not been documented. Determination of whether the decline of spawning activity during colder periods are due to metabolic effects or associated with embryo survival is important for defining the potential effects of groundwater seepage on nest placement.

Dissolved Oxygen

The similarity between spring and nest dissolved oxygen concentrations provided further verification that nest water is exclusively influenced by the stream. Low groundwater DO levels may be factors determining avoidance of spring seepage areas as spawning sites. Spring water had low dissolved oxygen concentrations compared to both stream and nest samples (Fig.7). Developing embryos have a relatively high oxygen demand which would require avoidance of oxygen-depleted upwelling zones. Assessing the effects of pure spring seepage on embryonic development would necessitate experimental manipulations.

Chemistry

The only chemical parameter which differed appreciably from stream ambient levels was the ammonia concentration within the nest. High ammonia levels within the nest were likely due to embryonic waste products (Goetz, personal communication.) The thermal and chemical characteristics of the actual spawning

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pockets has not yet been documented. Consequently the reasons for increased levels of any chemical parameter are conjectural.

Implications

Previous studies assert that spawning nest structure is designed to maximize influence by stream water but fail to define the hydrologic regime within the nest (Vives 1990, Miller 1964). The minimal variation of temperature and chemistry between the nest spawning cup and the stream water column attest to the active interface between the stream and spawning cup. Stream flow seems to control these parameters within the nest.

Descriptions of cyprinid spawning nest-site preference typically have focused on substrate composition, current velocity, and water depth (Vives 1990, Becker 1983, Matthews 1985, Miller 1964). Studies of *Nocomis biguttatus*, *Luxilus cornutus*, and *Semotilus atromaculatus* report highest preferences of gravel substrate (27%, 24%, and 23% respectively) (Becker 1983). Areas with predominantly mud and silt substrates were infrequently chosen as nesting sites (Becker 1983). Current velocity is also interpreted to be an important criterion for nest placement (Vives 1990, Becker 1983, Miller 1964). All three species are noted to choose areas with current flow faster than the stream average (Miller, 1964).

The infrequency of strong spring influence in regions with appropriate spawning substrate, water depth, and adequate current velocity prevent conclusive assessment. Avoidance of midchannel spring seepages at two sites with appropriate spawning substrate (Fig.2) may have occurred coincidentally. Verifications of avoidance should be proven by comparing total areas of substrate use, with total area of suitable nesting habitat influenced by upwelling groundwater, and total area of streambottom. The sites of minor substrate temperature depression on transects 20-35m were also not selected by spawning minnows. The case for spring avoidance in site selection is indirectly supported by temperature and DO characterizations of the spawning cup. Whether cyprinid spawning-site preference would be altered by the occurrence of spring seepage, or a strongly groundwater-influenced hyporheic zone needs further investigation.

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