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Field Testing of New Monitoring Protocols to Assess Brown Trout Spawning Habitat in an Idaho Stream

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Abstract.—The effects of nonpoint source pollution on salmonid incubation and embryo survival to emergence were evaluated on Rock Creek in south-central Idaho. New monitoring protocols were applied to evaluate effects of sediments and associated pollutants on spawning and recruitment of brown trout *Salmo trutta.* According to these new protocols, incubation success in artificial egg pockets is measured in terms of intragravel dissolved oxygen (IGDO), percent fine sediment (<2.0 mm) in the substrate, and survival of embryos and alevins to emergence. Mean IGDO concentrations and saturation levels were significantly less ($P < 0.05$) at stations affected by agricultural pollutants than at a control station. Up to 40% of IGDO measurements were below 6.0 mg/L, the proposed water quality criterion for salmonid spawning in Idaho streams. Mean values for percent fine sediment were also higher at all impacted stations. Survival to emergence at the control station ranged from 18 to 83% and averaged 48%. Survival at impacted stations ranged from 0 to 54% and averaged 17%. Survival generally increased with mean IGDO concentrations above 8.0 mg/L and 70% saturation. A growth index expressed as the ratio of alevin total length to thermal units of exposure (summed daily degrees above 0°C) during stream incubation showed reduced alevin growth during incubation at impacted stations. Significant positive relationships were found between IGDO saturation and survival to emergence ($P < 0.01$). We found significant inverse relationships for percent fine sediment and survival ($P < 0.05$).

Water quality management programs conducted under state and federal legislation have identified nonpoint source pollution as a major obstacle to attaining the "fishable–swimmable" water goals of the Clean Water Act (Karr 1991). In Idaho, nonpoint sources of pollution are regulated according to impacts on specific beneficial uses. Salmonid spawning is a designated beneficial use common in the streams of Idaho (IDHW 1985). Because salmonid spawning is one of the most sensitive beneficial uses impaired by nonpoint source pollution, impacts on spawning habitat have become a primary focus in water quality monitoring programs in Idaho. Nonpoint source activities generate fine sediments, which may seriously threaten survival of embryonic salmonids (Chapman and McLeod 1987).

Fine sediment reduces the flow of water through spawning gravels, effectively reducing the amount of dissolved oxygen (DO) delivered to incubating fish eggs (Cordone and Kelly 1961; Shumway et al. 1964). Survival to emergence tends to decrease as the amounts of fine sediment increase in the incubation environment (Chapman 1988).

Grost et al. (1991a) found that fine sediment (<0.85 mm) accumulated in the egg pockets of brown trout *Salmo trutta* during winter incubation. Oxygen levels required for salmonid embryo survival and alevin emergence have been well established from laboratory results (Alderdice et al. 1958; Shumway et al. 1964; Mason 1969). A few field studies of intragravel dissolved oxygen (IGDO) and salmonid survival conducted by Wickett (1954) and Coble (1961) support the validity of the laboratory results.

As an Idaho water quality criterion (IWQC), Harvey (1989) recommended a minimum of 6.0 mg IGDO/L for the protection of Idaho streams that support salmonid spawning. The U.S. Environmental Protection Agency (USEPA 1986) suggested a minimum criterion of 5.0 mg/L to protect early life stages of coldwater biota. Chapman and McLeod (1987) concluded that IGDO in egg pockets should exceed 76% of saturation at 0–10°C for protection of a salmonid fishery.

Techniques are needed to assess conditions in the egg pocket because they control salmonid in-

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cubation and emergence (Chapman and McLeod 1987; Wesche et al. 1989). Most prior research relating survival to emergence, fine sediment, and DO has been in artificial streams (Bjornn et al. 1977; Witzel and MacCrimmon 1983). Information developed in the laboratory may not reflect the dynamics of a natural stream.

The lack of relatively simple, reliable, and standardized field methods of characterizing the quality of salmonid spawning habitat has delayed the application of standards and criteria needed to protect streams from sedimentation. Bjornn and Reiser (1991), in their comprehensive summary of the literature, indicated the lack of data available for the egg pocket or spawning redd. The intragravel technique used by Hoffman (1986) appears to be an effective method to measure IGDO in the natural incubation environment. Burton et al. (1990) developed measures of salmonid egg incubation success in relation to fine sediment accumulation in artificial redds. Their technique has been tested by Burton et al. (1990) and King and Thurow (1991), who indicated that although the exact morphology of natural redds is difficult to mimic, IGDO concentrations, temperatures, and fine sediments in artificial redds were not significantly different from those in nearby natural redds.

This paper describes a comprehensive field procedure that integrates the methods of Hoffman (1986) and Burton et al. (1990) to assess and monitor the effects of sediment on salmonid spawning. We measured the survival of brown trout embryos in relation to the proportion of fine sediment in the substrate and IGDO. Our objectives were (1) to evaluate relationships between percent fines, IGDO, and embryo survival so that resource impairment can be predicted, and (2) to evaluate whether nonpoint source pollution affects salmonid spawning habitat in Rock Creek, Idaho. This study was designed to determine if stations affected by various levels of nonpoint source pollution exhibited impaired spawning habitat when compared with an upstream control station.

Study Area

Rock Creek in Twin Falls County, south-central Idaho (Figure 1) lies within the Snake River Plain–High Desert ecoregion (Omernik 1986). Rock Creek begins in the Sawtooth National Forest and flows northwesterly for 78 km to the Snake River. The watershed covers 80,292 hectares, 21,003 hectares (26%) of which are irrigated cropland. Grazing impacts are common throughout the watershed. Mean annual precipitation is about 29 cm. Elevation ranges from 1,128 m above mean sea level at station S-3 to 1,524 m at station S-8 (Figure 1). Soils in the study area can be generally described as productive and highly erodible silt–loams, which are underlain with fractured basalt.

Rock Creek has been intensively monitored by the Idaho Department of Health and Welfare, Division of Environmental Quality (IDHW–DEQ), from 1981 to 1990 as part of the U.S. Department of Agriculture National Rural Clean Water Program to assess the effectiveness of a program to abate nonpoint source pollution resulting from irrigated agriculture. Important designated uses that have been affected by agricultural activities include spawning by both brown trout and rainbow trout *Oncorhynchus mykiss* (IDHW 1989). Best management practices—which include uses of sediment basins, grassed waterways, conservation tillage, animal waste controls, and improved water conveyance systems—have been applied to approximately 75% of the critical areas of the watershed. Monitoring by the IDHW–DEQ has shown that irrigation returns and streambank erosion have contributed large amounts of suspended sediment and phosphorus to the stream. Seven small trout hatcheries are located at perennial springs along the lower portion of Rock Creek and may be contributing organic sediments high in oxygen demand (Maret 1990).

Flow is low in summer and fall but high in the spring from winter snowmelt and runoff. Base flows measured in Rock Creek during the study period ranged from 0.28 m^3/s at the upper end of the study area to 1.39 m^3/s at the downstream end. Stream widths at study stations ranged from 5.2 to 12.2 m. Gradient at all stations is less than 1.0%.

According to Evermann (1894) chinook salmon *Oncorhynchus tshawytscha* and steelhead (anadromous rainbow trout) used Rock Creek for spawning prior to construction of main-stem dams on the Snake River. Presently, lower Rock Creek supports both brown and rainbow trout populations that are heavily supplemented by hatchery fish because of a lack of natural recruitment. The headwater area, also stocked with these species, has more natural recruitment of trout (Maret 1990). The remainder of the fish community in the study area is composed of speckled dace *Rhinichthys osculus,* redside shiner *Richardsonius balteatus,* chiselmouth *Acrocheilus alutaceus,* mottled sculpin *Cottus bairdi,* mountain sucker *Catostomus platyrhynchus,* bridgelip sucker *Catostomus columbianus,* and largescale sucker *Catostomus macrocheilus.*

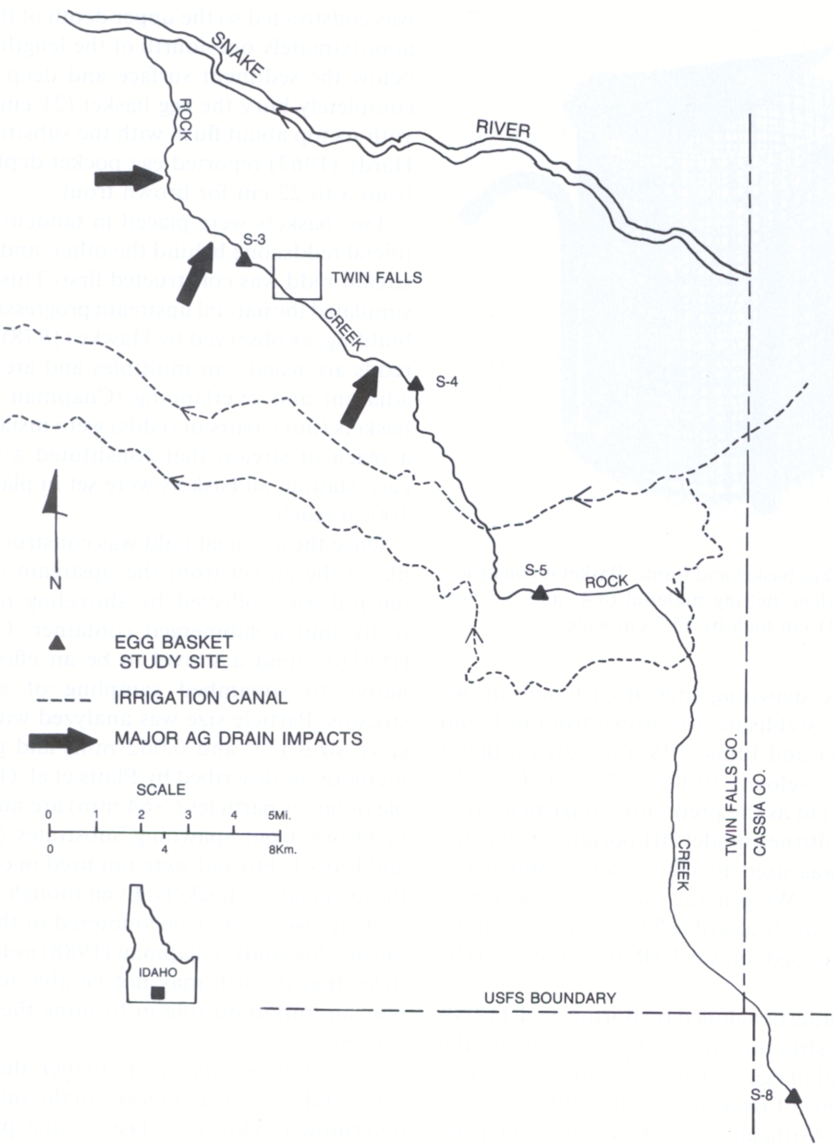

FIGURE 1.—Sampling station locations on Rock Creek, near the town of Twin Falls, Idaho. Arrows indicate major agricultural (AG) irrigation return flow areas. County (CO.) lines and U.S. Forest Service (USFS) boundary are shown.

Methods

Four study sites were selected (Figure 1) to represent the range of impacts that potentially impair salmonid spawning in Rock Creek. A minimally impacted, upstream station (S-8) was selected to serve as a control. All other stations were selected downstream of known land-use impacts on water quality: S-5 had grazing and streambank erosion impacts; S-4 had grazing and moderate agricultural return flow; and S-3 had cumulative impacts from grazing, agricultural return flows, and all other pollution sources (i.e., fish hatcheries and animal confinement operations). Sites S-1, S-2, S-6, and S-7 are stations that were not sampled for this study but were previously established as part of a water quality monitoring network by the IDHW–DEQ.

Field measurements began November 15, 1989, when water temperatures approached 7–9°C, the approximate temperature range at which brown trout are most likely to spawn (Mansell 1966). To

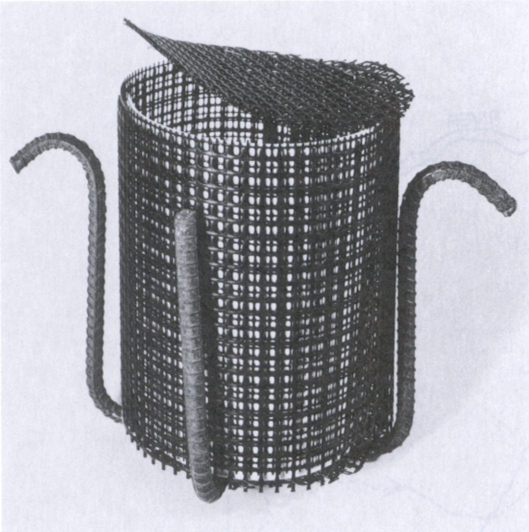

FIGURE 2.—Egg basket and frame. Basket is constructed of polyethylene netting material (6.4- and 3.2-mm mesh) and is 21 cm high by 15.2 cm wide.

select specific spawning sites at each station, we used criteria established for brown trout in Idaho by Cochnauer and Elms (1986) for stream depth (0.15–0.3 m), velocity (0.17–0.22 m/s), and substrate (0.3–7 cm as the predominant particle size). A Marsh–McBirney model 201 portable water current meter was used to take velocity and depth measurements. We generally located sites at pool tail-outs or at the heads of riffles where the channel bed gravel sloped upward (Reiser and Wesche 1977).

The technique developed by Burton et al. (1990) requires construction of artificial redds in the stream, burial of egg baskets containing eyed eggs, and placement of oxygen sampling tubes next to the baskets. Artificial redds were constructed by using a shovel to excavate the egg pocket at selected sites. Gravel was lifted up into the stream and released to simulate the action of the spawning female. This action is associated with a natural "cleaning" of fines from the substrate material so that egg pockets are initially lower in fines than surrounding substrates, as observed by Chapman (1988), Young et al. (1989), and King and Thurow (1991). A depression and downstream tailspill were formed by repeating this procedure. Dimensions of the artificial redds were based on total lengths of spawning brown trout females (range, 30–45 cm). The long axis of the depression was oriented with the current, and was approximately two times the length of the spawning female. The egg pocket was constructed so the upper depth of the eggs was approximately one-fourth of the length of the fish below the sediment surface and deep enough to completely bury the egg basket (21 cm in height) with its top about flush with the substrate surface. Hardy (1963) reported egg pocket depth to range from 8 to 22 cm for brown trout.

Two baskets were placed in tandem in two artificial redds, one behind the other, and the downstream redd was constructed first. This procedure simulated the natural upstream progression of redd-building, as observed by Hawke (1978). In nature, redds are usually in multiples and are frequently adjacent and overlapping (Chapman 1988). Six baskets (three pairs of redds) were installed within a reach of stream that constituted a station. At each station, all baskets were set in place within a 100-m reach.

Once the artificial redd was constructed, a sample of the gravel from the upstream edge of the tailspill was collected by shoveling material directly into a submerged container. Grost et al. (1991b) found a shovel to be an effective alternative to streambed sampling of small trout streams. Particle size was analyzed with standard sieve sizes (2.0 and 0.062 mm) and gravimetric methods, as described by Platts et al. (1983). Cobble or larger particles (>64 mm) are not abundant in brown trout spawning substrates (Cochnauer and Elms 1986) and were not used in constructing the artificial egg pockets. Even though these larger particles were rarely encountered in the substrate during this study, Chapman (1988) noted that particles that the fish may not be able to move can play an important role in forming the egg pocket centrum.

Percent fines—particles smaller than 2.0 mm (sand and smaller particles)—in the substrate were determined. This size-class of fine particles has been demonstrated to affect salmonid spawning (Hausle and Coble 1976; Reiser and White 1988). Sterling (1983) determined by particle size analysis that deposited sediments in Rock Creek were predominantly sand and silt.

Egg baskets were cylinders constructed of two layers of polyethylene mesh (Figure 2). The heavier 6.4-mm mesh was placed on the outside of the cylinder. The inner 3.2-mm mesh was used to ensure that alevins would not escape. Baskets were 21 cm high and 15.2 cm in diameter. Circular tops and bottoms were fabricated from the same mesh sizes. Metal frames fashioned from 0.95-cm-thick steel bar were used for support and for retrieving the baskets.

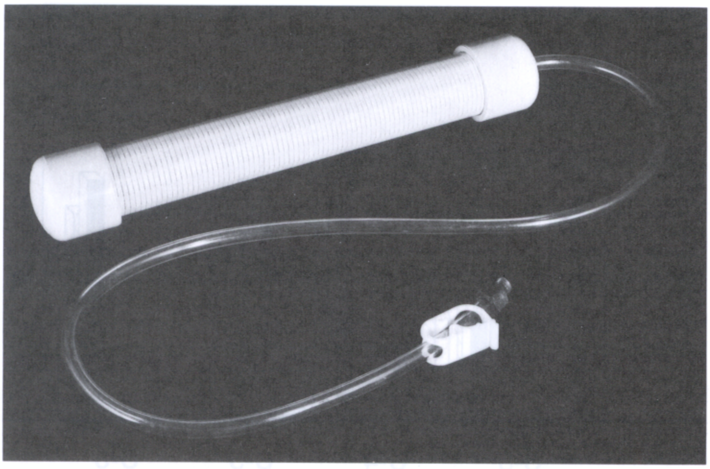

FIGURE 3.—Intragravel dissolved oxygen monitoring probe, 30.5 cm long and 3.2 cm in diameter.

The baskets were filled one-half full with gravel from the tailspill formed by constructing the artificial redd. Substrate materials were derived directly from the constructed tailspill with minimal, if any, loss of fines. Grost et al. (1991a) found that substrate samples collected during winter from tailspills of brown trout redds were not significantly different from substrate in the egg pockets.

Eyed brown trout eggs were placed near the center of these baskets and the baskets and IGDO sampling tubes were buried within constructed depressions in the streambed. To mimic natural conditions, burial was accomplished by excavating and lifting into the streamflow streambed gravels from immediately upstream of the egg pocket depression. This basket installation process produces another depression upstream for placement of a second basket, and the burial of the second basket produces a third depression, which approximates the morphology of a natural redd. Baskets and IGDO tubes were set in place over a 2-d period to ensure that fresh eggs were used.

Intragravel dissolved oxygen was monitored with a sampling device similar to that described by Hoffman (1986). In this study, IGDO was defined as the oxygen concentration in the interstitial water collected from 10–20 cm below the streambed surface, the approximate depth of the buried eggs. Well screen with 0.152-mm continuous slots formed the probe (30.5 cm long, 3.2 cm diameter; Figure 3). An inner, 0.95-cm-diameter plastic pipe, perforated in three locations with 0.16-cm holes, was positioned inside the screen and stabilized by 3.2-cm-diameter schedule-40 polyvinyl chloride (PVC) caps on either end. The internal pipe was connected to approximately 91-cm-long, 0.95-cm-diameter Tygon plastic tubing through a hole in one PVC cap. The tubing was fitted at its end with a clamp to ensure that the pipe remained free of obstructions. The placement of the IGDO sample tube was horizontal, as close to the eggs (midbasket depth) as possible, just before the baskets were buried. One tube was placed directly behind the upstream basket for each pair of artificial redds. The Tygon plastic tubing leading from the IGDO pipe had to be sufficiently long to clear the highest water surface to facilitate IGDO sampling.

A hand-held peristaltic pump was used with a battery-operated drill to retrieve samples for IGDO and temperature. An amount of water equaling the inside volume of the connecting and internal tubing (approximately 200 mL) was extracted prior to sampling. This same volume was then slowly pumped out for approximately 1 min into a small plastic bottle for immediate measurement. Surface dissolved oxygen (DO), IGDO, and temperature were measured biweekly with a YSI model 54A meter, calibrated prior to each use. Surface DO and IGDO were measured to the nearest 0.1 mg/L and temperature was measured to the nearest 0.5°C. Percent saturation was determined for each DO concentration to reduce the effects of altitude and water temperature differences among stations. Interchange of surface and intragravel water was indexed as a percentage, calculated from the ratio of mean IGDO concentration and surface DO concentration (Woods 1980).

Leitritz and Lewis (1976) determined that emergence of various salmonid species can be estimated with thermal units (TU; the accumulated differ-

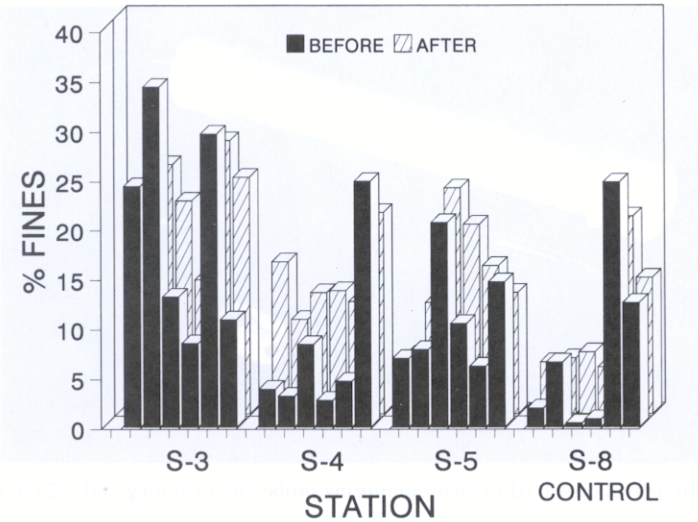

FIGURE 4.—Comparison of percent fines (<2.0 mm), before instream (November 15, 1989) and after instream incubation (January 29 or March 6, 1990), for the six baskets (artificial redds) used at each station in Rock Creek. Differences were not significant ($P > 0.05$).

ence between between mean daily temperature and 0°C). Accumulated thermal units (summed daily mean degrees between 0°C) were estimated by plotting incubation days and temperature. The eggs, obtained from the Spring Creek Hatchery in Lewistown, Montana, hatched at approximately 378 TU (T. Nowak, Spring Creek Hatchery, personal communication). This was used as a target to determine removal of the baskets. Witzel and MacCrimmon (1983) found similar requirements for initial emergence of brown trout, which occurred between 406 and 420 TU. Eggs were set in the baskets on November 15, 1989, and hatched after 75–111 d of instream incubation. Eggs planted at stations S-3 and S-4 were estimated to hatch earlier than those at stations S-5 and S-8 because warmer spring sources in the lower reaches of Rock Creek caused thermal units to accumulate faster there. We did not have an estimate of hatchery mortality, so we assumed that survival of the eyed eggs used in the field equaled 100%. This assumption may be in error, so in future use of this technique, percent mortality should be measured.

Nonparametric statistics were used, because DO displayed nonnormal frequency distributions. The Mann–Whitney U-test tested the differences between control and impacted sites. The Wilcoxon signed-rank test, analogous to the matched-pairs t-test, was used to test the differences between percent fines in baskets before and after incubation (Sokal and Rohlf 1981). Spearman's nonparametric correlation coefficients (rho, calculated by the Number Cruncher Statistical Package, version 5.01) were used to evaluate relationships between variables (Snedecor and Cochran 1967).

Results

Percent Fines

Percent fines in gravel beds vary spatially and temporally because of the dynamic nature of streams (Chapman 1988). However, during this study mean percent fines (<2.0 mm) did not change significantly within the artificial redds during the time period sampled (Figure 4). Two baskets (one each at S-4 and S-8) were omitted from the analyses because the substrate surrounding both baskets was scoured away, exposing them to the open channel. Mean percent fines did increase at each station during the incubation period, but not significantly. A Wilcoxon paired t-test of mean percent fines for all stations showed no significant difference ($P > 0.05$) during the incubation period. The slightness of the increase appears to be attributable primarily to the sand caps (2–4 cm in depth) that were particularly evident at stations S-3, S-4, and S-5. This capping appeared to reduce the deep intrusion of fine sediment into the artificial egg pocket during the incubation period.

Variability of percent fines within each station was high for all substrate samples. The coefficient of variation (SD/mean) for percent fines ranged

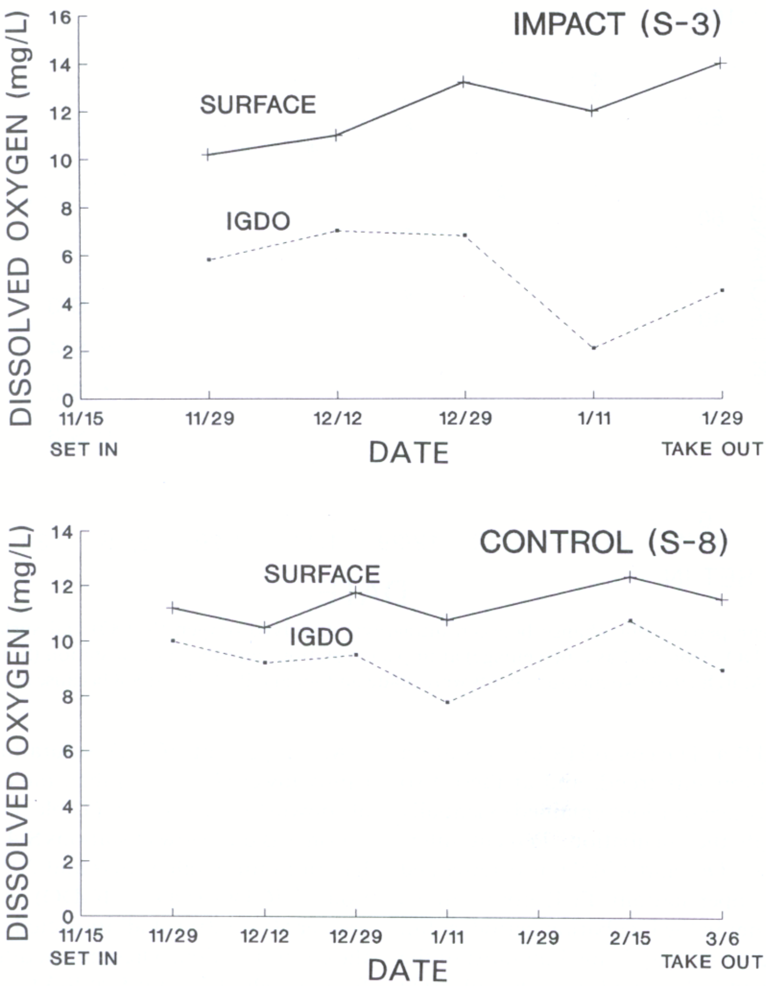

FIGURE 5.—Temporal changes in surface dissolved oxygen and intragravel dissolved oxygen (IGDO) concentrations at an impacted station (S-3) and at the control station (S-8) in Rock Creek during the study period, November 1989 to January or March 1990. No measurements were made on January 29, 1990, at S-8 because of access difficulties.

from 38% at station S-3 to 93% at station S-8. The high coefficient of variation at station S-8 is attributed to the heterogeneity of substrate sizes at this unimpacted station.

The percent fines (<2.0 mm) at the beginning and after the incubation period were pooled, and the Mann–Whitney *U*-test was used to compare each station to the control (S-8). Mean percent fines at stations S-3 and S-4 were significantly greater ($P < 0.05$) than at the control station (S-8). Mean percent fines (<2.0 mm) were 21.0% at S-3, 16.2% at S-4, 12.8% at S-5, and 9.0% at S-8. Fines smaller than 0.062 mm (silt and clay) made up a small portion (<2%) of each sample by weight.

Oxygen

As expected, there was no significant difference ($P > 0.05$) in mean surface DO concentrations between stations. However, mean IGDO concentrations at stations S-3 and S-4 were significantly lower ($P < 0.05$) than the control station mean (Table 1). Minimum concentrations were unusually low; values of 1.0 and 2.1 were recorded for stations S-4 and S-3, respectively. Figure 5 shows examples of surface DO and IGDO over time at an impacted station and the control station. The data show that IGDO declined through time at the impacted stations. This trend was typical at

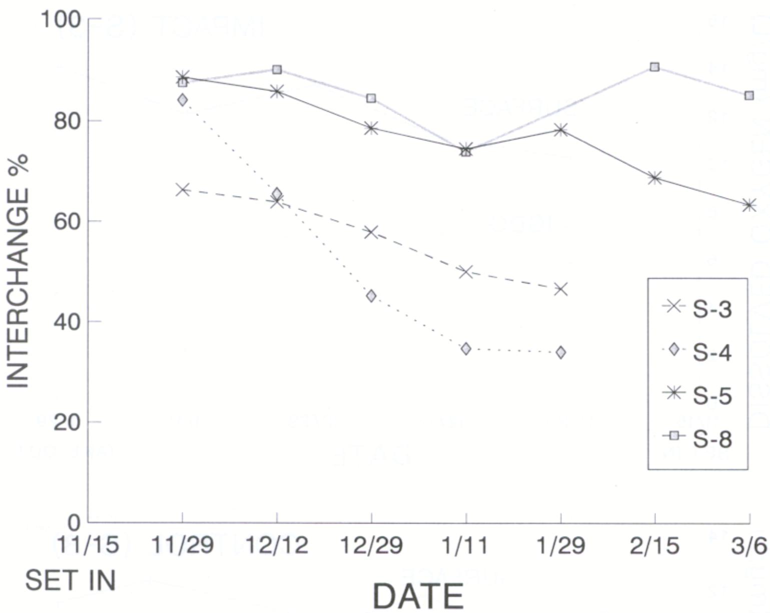

FIGURE 6.—Mean percent interchange between intragravel dissolved oxygen (IGDO) and surface DO (ratio of IGDO to surface DO, expressed as a percentage) at impacted stations and the control station (S-8) in Rock Creek, November 1989–March 1990. No measurements were made on January 29, 1990, at S-8 because of access difficulties.

stations S-3 and S-4. The control (S-8) and station S-5 did not exhibit this trend, and at these two stations IGDO concentration remained essentially constant through the incubation. Percent interchange of surface DO and IGDO also remained high at the two upper stations. Field observations indicated that later in the incubation period, a thin cap of sand (<2.5 cm) had formed on most of the baskets at S-3 and S-4. In addition, the substrate appeared to be high in fine organic material at these stations. A combination of sand capping, which may have impeded flow, and oxygen demand of the sediments may have caused the gradual decline in IGDO later in the incubation period.

Mean percent IGDO saturation was significantly lower ($P < 0.05$) than the control value at all downstream stations (Table 1). Percent saturation was quite low at stations S-4 and S-3, which had minimum values of 9 and 20%. Mean depletion of IGDO (DO − IGDO) was significantly greater ($P < 0.05$) at all impacted stations than at the control station. These mean differences ranged from a high of 7.2 mg/L at S-3 to 2.8 mg/L at S-5 (Table 1).

All impacted stations downstream from the control had some measured IGDO concentrations below the proposed IWQC (Figure 7). The proportion of IGDO measurements below the proposed

TABLE 1.—Surface dissolved oxygen (DO) and intragravel dissolved oxygen (IGDO) conditions at Rock Creek sampling stations, 1989–1990. Ranges are in parentheses; *N* = number of DO measurements. An asterisk indicates a mean significantly different ($P < 0.05$) from the mean for the control station (S-8).

Station	*N*	Mean surface DO (mg/L)	IGDO (mg/L) Mean	IGDO (mg/L) SE	Mean IGDO (% saturation)	Mean difference (DO − IGDO, mg/L)
S-3	13	12.1 (10.0–14.0)	6.7* (2.1–9.6)	0.52	63* (20–92)	7.2* (2.4–9.9)
S-4	15	11.7 (11.1–12.6)	6.1* (1.0–10.0)	0.93	54* (9–89)	5.6* (1.2–11.2)
S-5	20	10.1 (10.8–13.2)	9.1 (5.4–11.0)	0.32	77* (52–99)	2.8* (0.8–6.8)
S-8 (control)	14	11.4 (10.5–12.4)	9.8 (7.8–11.6)	0.26	85 (73–95)	1.6 (0.7–3.0)

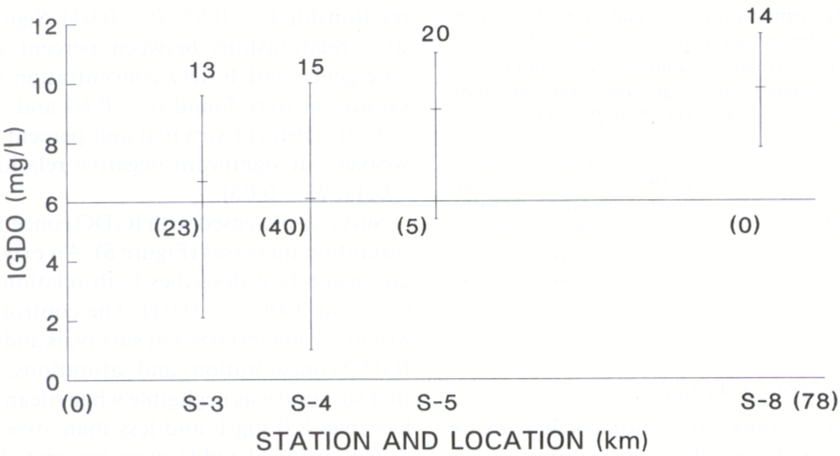

FIGURE 7.—Means and ranges of intragravel dissolved oxygen (IGDO) concentrations at each station (S), 1989–1990. The number above each vertical bar is the number of observations, and the number in parentheses by each vertical bar is the percentage of IGDO concentrations below the proposed IGDO standard of 6.0 mg/L (Harvey 1989). The horizontal axis expresses the relative distance (in kilometers) between stations along Rock Creek.

standard ranged from 5 to 40% for these stations. However, the mean IGDO did not go below the IWQC at any station.

Survival and Growth

Survival to emergence was highest at the control station (S-8), where it ranged from 18 to 83% and averaged 48% (Table 2). Survival at downstream impacted stations S-3, S-4, and S-5 ranged from 0 to 54% and averaged 4, 17, and 14%, respectively. Eggs in 7 of the 17 baskets at these stations had no survival. Baskets with no or low survival typically had white egg masses that were in late stages of decomposition.

TABLE 2.—Incubation period and success of brown trout embryos and alevins incubated in artificial redds at four sampling stations in Rock Creek. Ranges are in parentheses. Eyed eggs were planted on November 15, 1989.

Station	Mean % survival to emergence	Mean total length (mm)	Instream incubation period (d)	Mean temperature (°C)	TU[a]
S-3	4 (0–9)	23.1 (21–25)	75	7.3 (6.0–8.0)	548
S-4	17 (0–54)	20.6 (19–23)	75	5.0 (3.0–6.0)	375
S-5	14 (0–44)	22.6 (20–25)	111	3.1 (0.0–8.0)	344
S-8 (control)	48 (18–83)	22.1 (17–25)	111	2.6 (0.0–5.0)	289

[a] TU = thermal units of exposure. Each value includes 100 TU of exposure at hatchery prior to incubation instream.

Surviving alevins at all stations usually had little or no yolk sac remaining. Nine of 17 baskets at the impacted stations contained dead alevins in various states of development. This was not the case at the control (S-8), where only one basket had two dead, partially developed alevins.

Despite colder ambient water temperatures, growth in total length of alevins at station S-8 was comparable to that of alevins at the downstream stations (Table 2). Mean total lengths of alevins ranged from 20.6 to 23.1 mm for all stations. The growth index (ratio of mean total length to thermal units of exposure) gradually increased from the downstream station (S-3) to upstream station (S-8) (Table 3). Alevins at the control station (S-8) exhibited almost twice the growth per thermal unit as alevins at the impacted downstream station S-3. Mean IGDO also generally increased upstream, as already noted (Tables 1, 3).

TABLE 3.—Growth index for brown trout embryos, intragravel dissolved oxygen (IGDO) during incubation, and number of alevins surviving after instream incubation at four stations in Rock Creek.

Station	Growth index[a]	Mean IGDO (mg/L)	Number of alevins
S-3	0.042	6.7	20
S-4	0.055	6.1	98
S-5	0.066	9.1	84
S-8 (control)	0.076	9.8	238

[a] Ratio of mean total length (mm) of alevins to thermal units of exposure.

TABLE 4.—Spearman's rank correlation matrix for independent and dependent variables measured (N = 22 observations) in instream incubation experiments with brown trout embryos in artificial redds. Asterisks indicate significant r values (P < 0.05* or P < 0.01**).

Variable	IGDO, % saturation	% survival to emergence	% fines (<2.0 mm) in sediment
IGDO concentration (mg/L)	0.97**	0.64**	−0.47*
IGDO, % saturation		0.66**	−0.46*
% survival to emergence			−0.47*

Relationships between Variables

All Spearman's rank correlation coefficients for the four measured variables were significant (Table 4). As expected, IGDO concentration and IGDO saturation had a highly significant positive relationship (r = 0.97; P < 0.01). Significant positive relationships between percent survival to emergence and IGDO concentration and IGDO saturation were found (r = 0.64 and r = 0.66; P < 0.01). Percent survival and percent fines had a weaker but significant negative relationship (r = −0.47; P < 0.05).

Survival increased with IGDO concentration and saturation increases (Figure 8). An exponential relationship best describes both relationships (r^2 = 0.59 and 0.49; P < 0.01). The control station (S-8) had the highest percent survivals and the highest IGDO concentrations and saturations. We suggest that survival was negligible when mean IGDO was less than 8.0 mg/L and less than 70% saturation. A few artificial redds were associated with high mortality despite adequate IGDO, indicating that other factors besides DO also affect survival. The

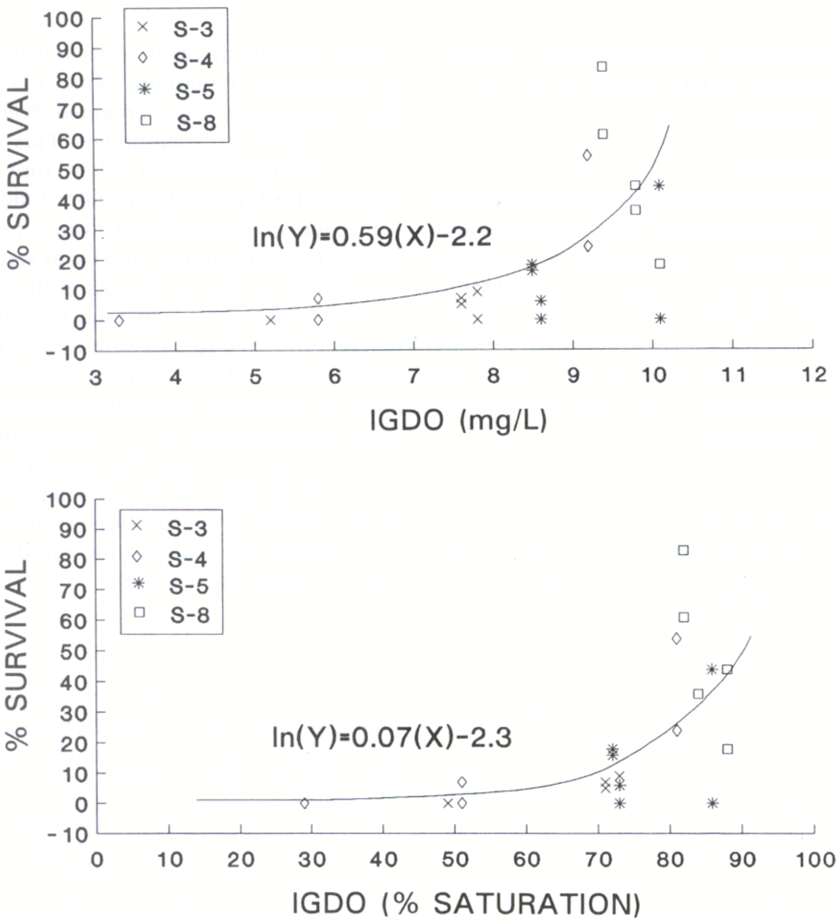

FIGURE 8.—Mean percent survival of brown trout to emergence (Y) versus intragravel dissolved oxygen (IGDO) levels (X), expressed as concentration (r^2 = 0.59) and percent saturation (r^2 = 0.49); ln = $\log_e$; N = 22 observations. Embryos were incubated in artificial redds at four stations (S) in Rock Creek, 1989–1990.

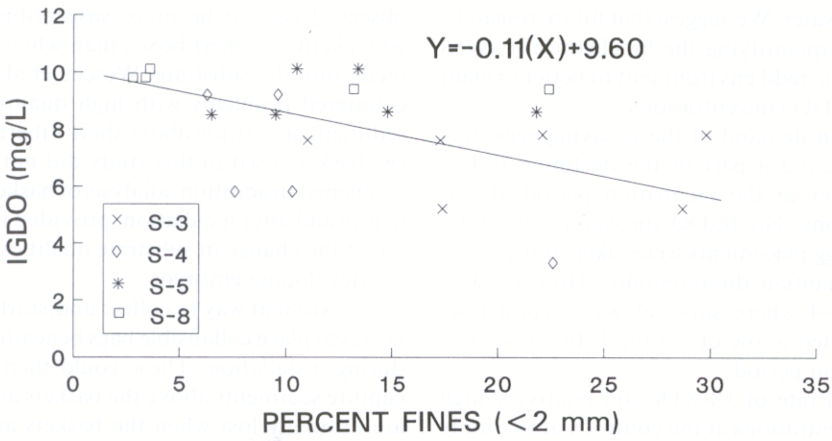

FIGURE 9.—Mean intragravel dissolved oxygen concentrations (IGDO) versus mean percent fines ($r^2 = 0.22$) at four stations (S) in Rock Creek, 1989–1990; $N = 22$ observations.

IGDO concentrations declined linearly with percent fines (Figure 9), although the relationship was not strong ($r^2 = 0.22$; $P < 0.05$).

Discussion

Our results suggest that inadequate IGDO concentrations, which result in poor survival and growth to emergence, impair brown trout spawning in lower Rock Creek. Stations S-3 and S-4 had IGDO concentrations significantly lower than those at the control station. In addition, 23–40% of the IGDO concentrations at these stations were below 6.0 mg/L, the proposed IWQC for the protection of salmonid spawning habitat. The data from this study also indicate that the IWQC of 6.0 mg IGDO/L may not be high enough, as indicated by relationships between IGDO and survival to emergence determined during this study.

As a result of applying best management practices to over 75% of the critical cropland areas in the watershed, suspended-solids loadings declined by as much as 78% at the lower end of Rock Creek between 1981 and 1989. Turbidity, nutrient levels, and bacteria levels also decreased during the same period (Maret 1990). Even though the water quality in the stream has improved, the data suggest these reductions have not been adequate to restore salmonid spawning in lower Rock Creek. Streambank erosion affects station S-5, upstream from the irrigation return water, and appears to have caused lower survival of embryos in the artificial redds at that location. However, IGDO concentrations at station S-5 were not as low as at downstream stations. At best, this part of Rock Creek would be expected to support only limited salmonid spawning.

Perhaps, as Reiser and White (1988) concluded, the major factor influencing egg mortality is the reduction of intragravel water velocities and concomitant reductions in IGDO caused by large amounts of fine sediment. Results of our field study suggest a strong relationship between survival and IGDO. Sowden and Power (1985) concluded that survival strongly depends on DO content in redds. Their field studies determined that mean IGDO concentrations should exceed 8.0 mg/L in the redds to ensure at least 50% survival during the preemergence stage.

The relationship between percent fines and IGDO shown in Figure 9 indicates that, under the assumption that a mean IGDO of 8.0 mg/L is required for survival and growth in Rock Creek, sediment with more than 15% fines may reduce IGDO concentrations to unacceptable levels for survival during incubation. Witzel and MacCrimmon (1983) found high survival to emergence of brown trout in artificial laboratory substrates containing less than 20% sand. Sand capping of the artificial redds observed at the lower stations may have prevented intrusions of additional fines deep within the artificial egg pocket.

Despite the variability of percent fines found during this study, excessive fines in the substrate appear to be at least a partial explanation for low DO concentrations. Other factors not measured, such as oxygen demand of the sediments, may also cause DO concentrations to fall below levels necessary to protect developing embryos. Hoffman and Scoppettone (1984) speculated that an important factor affecting IGDO within their artificial redds was the biochemical oxygen demand in combination with reduced exchange of oxygenrich surface water. We suggest that future researchers consider quantifying the biochemical oxygen demand in the redd environment to better explain observed IGDO concentrations.

The oxygen demand of the decaying eggs may also have played a part in the declining IGDO observed later in the incubation period at impacted stations. No IGDO measurements independent of egg placements were taken at these stations to substantiate this possibility. However, two baskets at S-4 where survival was highest (24–54%), indicated a low of 7.6 mg/L by the end of the incubation period.

A survival rate of 18–83% and relatively high IGDO concentrations at the control station imply that other unmeasured factors contribute to the mortality of developing embryos. Factors such as predation by macroinvertebrates, disease, and handling damage may have contributed to the wide range of survival at the control station. Use of eyed eggs in our study likely minimized the effects of disease and handling on developing embryos. Field sampling of natural redds has indicated that high losses may occur in the pre-eyed egg stage (Wickett 1954). These losses were attributed to a dependence on diffusion for oxygen, because the pre-eyed egg has not yet developed a circulatory system. Reiser and White (1988) also found higher survival in field tests with eyed eggs than with green eggs subjected to sediment with excess fines. Ideally, the egg and sperm source used in these field tests should also be from the stream where the field tests are conducted.

Most studies have used only one size-class to describe substrate fines. The size-classes most commonly considered are 0.84 mm (McNeil and Ahnell 1964; Reiser and White 1988), 2.0 mm (Hausle and Coble 1976), and 6.3 mm (Stowell et al. 1983). Criteria for fine sediments should clearly define the size-class and acceptable levels for a particular species during its appropriate spawning season. The percent fines used should also characterize the predominant fine particle sizes most likely to impair spawning. However, the levels may be difficult to characterize because of the large background variation in substrate composition (Adams and Beschta 1980). We found a weak inverse relationship between percent fines and IGDO ($P < 0.05$). Reiser and White (1988) found that a smaller size-class of fines (<0.84 mm) was most detrimental to embryo survival.

Harshbarger and Porter (1979) found that Vibert box plants induced sediment deposition because water movement was impeded. They also observed eggs to be more susceptible to fungus when kept in Vibert boxes than when planted directly into the substrate. Wesche et al. (1989) encountered problems with high quantities of fine sediment deposition above their Vibert boxes. The egg baskets used in this study did not have these problems. In addition, analysis of basket substrate, before and after incubation, provided information about the change in substrate quality surrounding the developing embryos.

An excellent way to collect undisturbed egg baskets is to place collapsible bags beneath egg baskets during installation. These could then be used to capture sediments above the baskets and fines that are normally lost when the baskets are retrieved from the stream. The bags, however, may partly restrict the delivery of oxygen by any upwelling currents that may exist in the substrate below the egg basket.

The basket could also be capped with a fry trap in the later stages of incubation to measure actual emergence from the substrate. This approach would give emergence survival estimates and evaluations of entrapment of emerging alevins.

Hoffman and Scoppettone (1984) concluded that the principal cause of mortality observed in their study of eggs of cutthroat trout *Oncorhynchus clarki* incubated in the Truckee River, Nevada, was the intolerably low concentrations of IGDO (below the USEPA minimum criterion of 5.0 mg/L). The application of these field protocols suggest IGDO can be effectively used to monitor the quality of salmonid spawning habitat. Establishing site-specific relationships between survival to emergence and IGDO can be particularly useful and defensible for monitoring water quality status and trends in view of nonpoint pollution abatement efforts. The monitoring of IGDO can also be used as a screening tool to identify potential problems in salmonid spawning habitat. These problems could then be further investigated with in situ studies of survival to emergence by using the artificial egg pocket technique.

Temperature did not differ between surface and intragravel water during this study. Temperature differences of 0.3–0.5°C have been found in other waters (Lorenz and Eiler 1989; Crisp 1990).

The gradual decline in IGDO concentration over time, especially in artificial redds with little or no survival, suggests that decaying embryos may create an oxygen demand. Future field studies should determine to what extent decaying embryos in artificial redds create IGDO depressions.

The protocols used in this study demonstrate that it is possible to relate environmental factors to survival in an artificial redd. The results of using these monitoring protocols indicate that salmonid spawning habitat of Rock Creek remains impaired despite long-term efforts to control nonpoint source pollution in the study basin. The approach presented in this study is objective and effectively simulates processes associated with salmonid incubation in the natal stream itself. For these reasons, we believe it represents an appropriate monitoring tool to evaluate specific environmental variables and survival to emergence within the artificial intragravel environment. However, further research on other salmonid species over a wider geographic area is needed to validate the use of these protocols for determining the quality of salmonid spawning habitat. In addition, further studies are needed to compare the environments of the artificial redd and the natural redd.

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