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SALMONID REDD DEWATERING:
WHAT DO WE KNOW?

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ABSTRACT

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Dewatering of salmonid spawning areas causes abrupt changes in the intergravel environment that may lead to extensive losses of development phases while intergravel in redds. Information on tolerance to dewatering and the extent of physicochemical changes in the gravel during dewatering can be used to assess potential impacts and to design and implement effective mitigation methods. Information generated by experimental studies at Pacific Northwest Laboratory (PNL) with fall chinook salmon is summarized, and comparisons are made with results from available literature. Potentially useful methods of mitigation are mentioned.

We found that prehatch phases (cleavage eggs and embryos) can be dewatered for several successive days and survive, but posthatch phases (eleutheroembryos and alevins) usually die within 24 hours. Survival of prehatch phases during extended dewatering requires maintenance of favorable intergravel temperature and moisture levels. Elevated temperatures (up to 22°C) can be tolerated for up to 8 hours without direct adverse effects, but freezing temperatures (-1.0°C or below) are lethal. Dewatered gravels must retain sufficient moisture to provide near 100% humidity for egg and embryo survival. In field situations, physicochemical conditions that limit survival in dewatered gravels include residual flow, temperature, gravel size and composition, and dissolved oxygen. Biological variables such as alevin behavior and certain species characteristics also influence survival.

INTRODUCTION

Large reservoirs have been constructed in many rivers to optimize in-stream uses (e.g., hydroelectric power production, navigation, fish passage), to provide water for consumptive uses (e.g., municipal supplies, irrigation, power plant cooling, industrial use), and to control flooding. The resulting water-level changes in streams used by spawning salmonids can expose redds buried in the gravel. In addition, drawdowns in lakes and reservoirs can expose areas used for egg deposition by shoreline spawners. In both situations, water may drain from the gravel. Losses of salmonid eggs and alevins from dewatering have been documented in the field in both river and lake ecosystems (Martin, 1955; Bayha and Koski, 1974; Washington State Department of Fisheries, 1976; McMullin and Graham, 1981; Stober and Tyler, 1982).

We initiated experimental studies on the effects of dewatering on intergravel development phases at PNL in the fall of 1979. The initial step was construction of an artificial redd system that would represent the intergravel environment and could be experimentally manipulated to simulate dewatering under field conditions. We subsequently conducted tests with four early development phases of fall chinook salmon (Oncorhynchus tshawytscha) under two regimes: daily, sequential dewaterings and one-time, extended dewaterings). We also examined the effects of temperature extremes and lowered intergravel moisture levels, and evaluated potential physicochemical changes and interactions that may occur in dewatered gravels.

This paper reviews our studies and synthesizes our results. Survival of young salmonids dewatered during embryogenesis depends primarily on the duration and extent of dewatering, the development phase present, and physicochemical alternations in the intergravel environment. Assessment of impact can be made accurately only on a site-specific basis because natural hydrographic conditions and other controlling factors are apt to vary seasonally at different locations. Effective mitigation efforts must also be planned, for similar reasons, on a site-specific basis.

METHODS

We conducted dewatering tests in artificial redds consisting of glass aquaria filled with a graded gravel mix (Becker et al., 1982, 1983). The basic experimental design used 30 redds per test, which were grouped in fives among six circular tanks located outdoors. Treatments for each test consisted of one variable (four different dewatering periods) and one control (no dewatering). Treatments were assigned randomly in each of the five tanks. Temperatures were monitored automatically in the five redds of one tank, the water bath of each tank, and the air (shade). Redds were supplied with filtered Columbia River water at a flow of 4 /min and maintained near 10°C. The aquaria were surrounded by a water bath that represented the temperature-moderating influence of gravel mass.

Four successive development phases were used in our tests: cleavage eggs (fertilized eggs), embryos (eyed eggs), eleutheroembryos (yolk-sac alevins), and pre-emergent alevins (button fry). Separation of development phases was based on an estimated 1000 temperature units (TU) from the time of fertilization to initial emergence, with TU calculated in degrees centigrade. With this scheme, about 250 TU were allotted to each development phase. Thus, dewatering of any one development phase was limited to about 20 days (e.g., 200 TUs). Chinook salmon eggs incubated at 10°C normally require about 51 days from fertilization to 50% hatch (Alderdice and Velson, 1978). This scheme permitted us to examine the relative tolerance of two prehatch phases and two posthatch phases to dewatering.

Tests involving thermal shock and moisture levels (Neitzel and Becker, accepted) were conducted separately. Thermal tests were conducted with all four development phases. Test groups were selected randomly from incubator stocks and placed directly in water heated or cooled to selected exposure temperatures (±0.1°C). Rearing temperature (e.g., acclimation level) was 10°C. Exposures were for 0, 1, 2, 4 and 8 hours, and exposed groups were reared separately in standard incubators until hatching or the possibility of delayed mortality was low (at least 2 weeks). Tests involving relative humidity were conducted with embryos in controlled environmental chambers. After chamber air was adjusted to programmed moisture levels, egg lots were dewatered by remote control for 0, 4, 8 and 24 hours and tnen rewatered, recovered, and reared several weeks in incubators. The relatively brief exposures used in these tests represented conditions that would result from dewatering when a hydroelectric dam operates in a power-peaking mode and water levels fluctuate daily.

In general, environmental conditions other than those planned in test treatments were controlled. For example, 10°C was used as a constant incubation temperature; the gravel mix in the artificial redds contained no fines; intergravel flow was sufficiently high during incubation to eliminate possible dissolved oxygen and metabolic waste problems; and thermal changes in dewatered redds were moderated by the water bath. Our tests were planned as generic studies to minimize possible site-specific differences and provide base-line information. Standardization of test procedures, therefore, provided us with data from consistently uniform test conditions. In field situations, dewatering regimes and physicochemical conditions in the intergravel environment will vary with site and event. Therefore, data from our tests may be conservative.

RESULTS

Effects of periodic dewaterings

The purpose of these tests was to determine the relative tolerance of four intergravel development phases of chinook salmon to daily dewaterings (Becker et al., 1982). Periodic dewatering is most likely to occur from a peaking power-production cycle at an upriver dam where power generation varies with power demand, which is primarily a day and night cycle. Tolerance was measured as survival rate after 20 consecutive dewaterings for periods up to 22 hours daily. The test design provided for rewatering of experimental redds for at least 2 h daily.

Prehatch development phases (cleavage eggs and embryos) were considerably more tolerant of daily dewaterings than posthatch phases (eleutheroembryos and pre-emergent alevins) (Fig. 1).

- Some cleavage eggs were killed by 12- and 16-hour daily dewaterings over 22 days, but this was primarily due to insolation and warming of exposed redd gravel in late September and early October

- Embryos survived up to 22-hour daily dewaterings over 22 days.

- About half the eleutheroembryos were killed by 4-hour daily dewaterings, and mortalities occurred early during the test period.

- Nearly all pre-emergent alevins were killed by 1-hour daily dewaterings, and mortalities occurred early during the test period.

These results indicated that, of the four development phases, embryos were the most tolerant to daily dewatering, followed by cleavage eggs. Accordingly, preliminary experiments with embryos and extended, one-time dewaterings were conducted. The experiments showed that embryos:

- tolerated multiple periods of longer dewatering (over 60% survival for four consecutive 118-hour periods).

- tolerated one-time dewatering for up to 12 days (over 80% survival).

Monitoring data indicated that intergravel temperature and moisture content (humidity) were factors influencing the survival of the eggs and embryos in artificial redds during dewatering. Growth among prehatch phases was delayed in some cases, indicating that the length of the daily dewatering period might adversely affect the size of survivors. This relationship was consistent for eleutheroembryos, but not for cleavage eggs.

Effects of extended dewaterings

The purpose of these tests was to determine the relative tolerance of each intergravel development phase of chinook salmon to extended dewatering (Becker et al., 1983). Extended dewatering may occur from reduction of stream flow to fill a new upstream reservoir, to permit construction or dredging activity along a river shoreline, or to fill reservoir depleted for irrigation or some other consumptive use. Tolerance was measured as survival rate after one-time dewatering lasting for periods from hours (intolerant posthatch alevin phases) to several days (tolerant prehatch egg phases). No provision was made in test design for occasional rewatering of exposed redds.

These tests confirmed that hatching represents the dividing line between relative tolerance and intolerance to dewatering of intergravel development phases. The results (Fig. 2) were generally comparable to the results obtained from daily, sequential dewaterings.

- Cleavage eggs tolerated one-time dewatering up to 12 consecutive days (98% survival), the maximum exposure period used for this development phase.

- Embryos showed similar tolerance when dewatered 12 consecutive days (92% survival), but tolerance declined progressively for lower dewaterings of 16 days (64% survival) and 20 days (53% survival).

- Eleutheroembryos tolerated only 6-hour dewatering (96% survival); nearly all died when dewatered for 48 consecutive hours.

- Pre-emergent alevins nearly all died when dewatered 6 consecutive hours.

Assessment of development data indicated no retarding effect on the development of cleavage eggs. However, premature hatching of embryos occurred under the longer, 16- and 20-day dewatering regimes (Fig. 3). Considerable mortality of embryos accompanied premature hatch. This indicated that hatching was a critical point for survival and that redds should be covered with water when hatching begins.

For most practical purposes, there was little difference in tolerance of the four development phases to daily, sequential dewatering and to one-time, extended dewatering. In field situations, the daily addition of water to a redd by periodic resumption of flow, as occurs with sequential dewatering, would help maintain favorable intergravel conditions, such as high moisture levels. Daily rewatering would also moderate intergravel temperature changes and refurbish supplies of bank-stored water that prolong intergravel flow during drawdowns.

Effects of temperature and moisture changes

Cessation of intergravel flow and drainage of water from the gravel are the first two consequences of reducing the water level. However, a number of physicochemical factors can influence survival during dewatering.

We examined the effect of temperature and moisture changes on early development phases of chinook salmon (Neitzel and Becker, accepted).

Temperature: Temperatures in dewatered spawning areas, after cessation of bank stored flows, are not moderated by the water mass either above or within the gravel. Therefore, intergravel temperatures in dewatered gravels can be expected to vary more widely than those in watered gravels because of diel changes in insolation and air mass. In most situations, temperatures can be expected to warm during the day and cool at night. Extremes of warming or freezing for relatively brief periods can be lethal or detrimental to intergravel eggs and alevins.

The purpose of our thermal tests was to quantify the upper and lower thermal tolerance limits for each of the four development phases on the basis of brief exposures. Tolerance was measured by survival and by appearance of gross abnormalities among eleutheroembryos.

Our data showed small but significant differences in tolerance to abrupt heat shock among the four development phases. Generally, no mortality or other direct adverse effects occurred at exposures of 22°C or below (Fig. 4). Above this point, effects appeared as a function of both temperature level and duration of exposure.

- Cleavage eggs were the most intolerant of dewatering; this was due, in part, to their characteristic sensitivity to handling and other physical trauma.

- Embryos were the most tolerant, surviving 8-hour exposures to 25°C and 2-hour exposures to 26.5°C.

- Eleutheroembryos and pre-emergent alevins tolerated 4-hour exposures to 23.5°C and 1-hour exposures to 25.0°C.

Most mortalities from elevated-temperature tests occurred during exposure or within the following 24 hours. Mortality during postexposure holding periods, including the hatching of cleavage egg and embryo test groups, was generally low. A few malformed individuals appeared after hatching among the egg and embryo exposure groups. The abnormalities were expressed as spinal deformations and failure of one or both eyes to develop.

Our data showed little difference in tolerance to abrupt cold shock among the four development phases. Generally, temperatures below -1.0°C were required to induce mortality (Fig. 4). Survival was high after exposure to near freezing temperatures (0.1°C) for 8 hours. Again, cleavage eggs showed some losses among all exposure regimes, including the control, because of their sensitivity to handling.

- Brief exposure to low, but non-freezing, temperatures did not cause lethal or sublethal effects among any development phase.

- Exposure to freezing temperatures for relatively brief periods did cause mortality.

We did not quantify precisely the effects of exposure to freezing temperatures. Presumably, the further the temperature below the freezing point (0°C), the more rapidly cellular contents of the egg or alevin will crystallize. Mortality of salmonid embryos subjected to freezing is well-documented in field situations.

Moisture: When streams or reservoirs are full of water, permeable substrates beneath them will also contain water. When water drains from the gravel during drawdowns, the interstices remain saturated with moisture. The air penetrating into wet gravel acquires essentially 100% relative humidity. The intergravel moisture inhibits prevents dehydration of egg stages, and facilitates continued transfer of oxygen across the egg membrane by diffusion (O'Brien et al., 1978). High moisture levels account for the survival and continued development of eggs and embryos during extended periods of dewatering (Reiser and White, 1981, 1983).

The purpose of our moisture tests was to examine and quantify the effects of relative humidity, which represents the moisture content of intergravel air, on developing embryos.

Results showed a clear relationship between saturation of air with moisture and embryo survival (Fig. 5). Survival of all embryos during 24-hour dewatering occurred only at 100% humidity. Exposure at lower levels of moisture content (for example, 90% relative humidity) resulted in gradual extraction of moisture and eventually in implosion of the embryo membrane.

- Survival of embryos (and probably cleavage eggs) during dewatering depends on retention of moisture in the gravel that provides near 100% humidity.

- Dehydration from exposed gravel surfaces that reduces intergravel moisture levels for periods of 4 to 8 hours can kill embryos.

- Embryos can survive up to 4 hour at relative humidities as low as 50%, if other conditions remain favorable.

We did not examine the effects of intergravel moisture on survival of eleutheroembryos and alevins because they tolerate only short periods of dewatering. Survival of posthatch phases requires intergravel water containing adequate amounts of dissolved oxygen.

Intergravel Conditions During Dewatering

The intergravel environment of salmonid spawning areas provides a set of physicochemical conditions that favor the incubation and hatching of eggs and the emergence of alevins. When spawning beds are dewatered, conditions in the gravel are abruptly altered. The extent and deviation of alteration will influence survival and will likely vary with site-specific hydrographic features. Our review of the literature leads to the following assessment.

There are seven primary factors that influence the survival of salmonid eggs and alevins in field situations when redds are dewatered (Fig. 6). We assessed these factors and their interactions from the literature (Becker and Neitzel, accepted), after examining the effects of temperature and moisture changes experimentally.

Residual Flow: Water drains from dewatered gravels at various rates. Given sufficient time, water may be lost and intergravel moisture levels may be depleted. When there is no drainage, water movement ceases and hypoxic conditions may develop. Water is replaced by air from the atmosphere when drainage occurs. Water usually drains more rapidly from coarse than fine materials. Bank storage represents prolonged intergravel flow from water stored underground at elevations above the stream bed. Gravel containing mixtures of fines tends to settle as water drains. These features are related primarily to physical conditions in different spawning areas.

Moisture Retention: Salmonid eggs can survive and develop provided they remain moist (Reiser and White, 1981, 1983; Neitzel and Becker, accepted) and if other intergravel conditions remain favorable. Moisture ensures that air entering the gravel has a high relative humidity, thus preventing dryness on the surface of the egg or embryo. Moisture can be lost from the surface of dewatered gravels from exposure to the atmosphere. Insolation will enhance dehydration and raise temperatures in the gravel. Overcast skies, shade and darkness may inhibit dehydration. Rain and moist snow may replenish moisture. Fine materials in the gravel mix can retard dehydration from the surface by limiting air circulation, and may help maintain moisture via capillary action from an underlying water table (e.g., Hardy, 1963; Hawke, 1978).

Temperature: Since temperatures in dewatered gravels are not moderated by water, they may vary more widely in response to diel changes in air temperatures and insolation. Extremes of warming that coincide with dewatering of redds can be detrimental or lethal to egg and embryo development. We found experimentally that chinook salmon eggs incubated at 10°C would survive abrupt transfer to 23°C water (heat shock) for 4 to 8 hours (Neitzel and Becker, accepted). These eggs also survived abrupt transfer to 0.1°C water (cold shock) for the same periods but did not tolerate freezing (-1.0°C). In most situations, exposed gravel will warm during the day and cool at night. However, an air mass sufficiently cold to cause freezing may persist independently of the day-night cycle and, thus, penetrate more deeply into dewatered gravels.

Mortality of salmonid eggs and alevins by freezing is well documented under experimental conditions (Brett and Alderdice, 1958; DeVries, 1971) and field conditions (Reiser and Wesche, 1979; McMullin and Graham, 1981).

Gravel Composition: Gravels used by spawning salmonids vary widely in structural composition. A high proportion of fines packed in gravel interstices may slow the rate of drainage during dewatering. Also, packed fines may form barriers that create standing pools of water over bedrock. Fines may also influence the depth and penetration of temperature changes in exposed redds. In general, the thermal gradient in the surface layer of coarse gravels is less than in fine gravels. If the overlying air mass is warmer or colder than the exposed gravel, fine interstitial materials will likely moderate the extent of temperature change in dewatered redds. The retention of moisture in fine materials via capillary action from below will also limit temperature change.

Dissolved Oxygen: When a gravel bed is dewatered, air enters from the atmosphere. The egg apparently is able to use oxygen from the air as long as the egg membrane remains moist. Moisture enables oxygen transfer by diffusion through the membrane. Thus, dewatered eggs can actually use oxygen from a moist environment for extended periods and continue to develop. Posthatch phases, however, lack this ability.

The phenomena of diffusion (O'Brien et al., 1978) may explain how eggs obtain oxygen in moist situations. The respiring egg acts as an oxygen sink, removing dissolved oxygen (DO) from the layer surrounding the egg membrane. In normal situations, DO is delivered to the egg by water, thus maintaining the oxygen gradient. In dewatered gravels, air replaces water in the delivery of oxygen, but the surface of the egg must remain moist for diffusion to be effective. This requires near complete saturation of intergravel air with moisture, thus maintaining high humidity content (Neitzel and Becker, accepted).

Hypoxic conditions may occur in standing water when drainage is incomplete, particularly when organic material is present. Respiring eggs deplete the available oxygen near their membrane in standing water, but alevins may circulate water with fins and supplement the DO supply to the gills (Fast et al., 1982). Ground water may also be deficient in oxygen. Replacement of oxygen in interstitial water that remains during drawdowns is restricted because air penetration or circulation is limited. Complete dewatering where air transfers oxygen into moist gravel layers is probably less detrimental to embryogenesis than hypoxic water.

Alevin Movement: Alevins have some ability to disperse in gravel to avoid dewatering or static water conditions. However, intergravel movement depends on alevin size and gravel composition. Large chinook alevins can make fewer successful migrations through large-sized gravel and no migration through small, medium, and mixed-size gravels compared with small coho salmon (O. kisutch) alevins (Fast et al., 1982). Rate of dewatering, extent of gravel permeability, and depth of the water table may also limit alevin movement as a survival mechanism. The survival span of posthatch phases is limited to about 24 hours or less during dewatering (Becker et al., 1982, 1983). Thus, survival of alevins through vertical or lateral movement is likely to be effective only during brief dewaterings. Sequential daily dewaterings may entrap alevins or otherwise prevent their emergence.

Species Characteristics: Different species of salmonids have slight, but distinct, biological attributes that may alter their susceptibility to dewatering. Three of these attributes are mentioned below.

First, eggs of different species develop at different rates at a given incubation temperature. Since the tolerance of eggs and embryos to dewatering is high as long as the environs is saturated with moisture, their combined tolerance corresponds roughly to the length of the prehatch period. Low temperatures slow the rate of embryonic development, thus extending the tolerance of prehatched phases to prolonged dewatering. Because temperature directly influences egg development, the tolerance of a species to dewatering will vary with its geographical distribution and spawning season.

Second, egg size (and possibly chorion thickness) may also influence tolerance to dewatering. Egg sizes vary considerably among salmonid species (Weisbart, 1968; Scott and Crossman, 1973). These attributes may effect diffusion of oxygen into the egg or embryo in damp gravel.

Third, different species of salmonids typically select gravels of different composition and bury eggs at different depths. Generally, eggs deposited deeply in gravel containing a high portion of fines will have greater protection from dewatering, dehydration, and temperature changes than eggs deposited otherwise. For example, chinook salmon redds are associated with deep pockets in coarse substrates (Burner, 1951; Platts et al., 1979), brown trout redds with shallow pockets in fine substrates (Ottaway et al., 1981), and kokanee salmon redds with surface deposits among cobble or rubble (Foerster, 1968).

DISCUSSION

Study results

Dewatering of salmonid redds during periods of intergravel development is a relatively new environmental concern. The event is associated with manipulation of water levels in streams, lakes and reservoirs by man. A few years ago, most fishery managers considered redd dewatering synonymous with total mortality of intergravel development phases. However, recent data suggest that salmon eggs and embryos (prehatch phases) are tolerant of dewatering when buried in gravels that retain suitable temperature and moisture levels. Eleutheroembryos and alevins (posthatch phases), because they require the presence of oxygenated water, may survive dewatering only a short time (up to 24 hours). Similar conclusions were reached independently by Reiser and White (1981, 1983) in outdoor studies conducted with steelhead (*Salmo gairdneri*) and spring chinook salmon eggs, and by Fast et al. (1982) in laboratory studies with chinook and coho salmon (*O. kisutch*) eggs and alevins.

Further experimental studies may be required to define more precisely the relative tolerance to dewatering among salmonid species. Our work was conducted with chinook salmon, a species with relatively large eggs (6-7 mm diameter). If egg size is an important factor, then our data may be unsuitable as tolerance limits for other species. Also, chinook salmon redds are generally placed deeper in the gravel than redds of other salmonids, and burial depth provides additional protection against thermal extremes and dessication during dewatering. On the other hand, a constant

10°C incubation temperature is unrealistic for field situations. Developing eggs of fall spawners will experience a change from moderate to low temperatures, and will develop more slowly during winter cooling. Developing eggs and embryos of late winter spawners will experience a change from low to moderate temperatures, and will develop more rapidly during spring warming. Thus, the effects of dewatering on intergravel phases of salmonids will vary with season.

Field studies that quantify physical conditions in dewatered gravels are limited. Clearly, physical conditions in gravels exposed to the atmosphere will change abruptly as water drains. The extent of these changes will strongly influence survival of developing eggs, embryos and alevins. Evaluation of potential impact and application of mitigation measures for effective protection during dewatering require a larger data base than now available. This data base should define physical changes in dewatered gravels under a variety of field situations. For the most part, physical conditions are apt to vary on a site-specific basis. A scheme for comprehensive field measurements should include gravel composition (permeability), intergravel flow rates (watered and dewatered situations), persistence of intergravel flow after drawdown (ground water or bank-storage flow), dissolved oxygen levels (flowing or standing water), and intergravel temperatures in relation to atmospheric conditions during gravel exposure. Extensive studies of this type were recently completed at Vernita Bar on the mid-Columbia River, Washington state (Chapman et al., 1981; Weitkamp et al., 1982) to establish a scientific basis for discharge regimes at Priest Rapids Dam.

Mitigation

Environmental considerations require that mitigation methods be planned for application when water levels are lowered enough to expose occupied redds. Such mitigation methods are relatively new. The contrasting tolerance of pre- and posthatch development phases provides a start for most deliberations. Therefore, the most direct mitigation procedure is to restrict dewatering to when eggs and embryos are present, and to avoid dewatering when eleutheroembryos and alevins are present. Extended spawning periods indicate that, in many field situations, pre- and posthatch phases may be present in the gravel bed simultaneously. In such cases, no dewatering should be permitted. Determining the hatching time may require both in-situ monitoring and calculation of the rate of egg development from spawning period and intergravel temperatures.

Other mitigation methods may be possible. Water-level fluctuations may be controlled during spawning periods to force adult salmonids to construct redds at deep locations (Chapman et al., 1981; Weitkamp et al., 1982). This assumes that suitable spawning areas are available at greater depths. Thus, occupied redds would be below the reach of subsequent drawdowns.

Hydroelectric power generation by a peaking operational mode will often cause daily fluctuations in stream flows that repeatedly dewater and rewater spawning areas. Daily dewatering will limit the total time of redd exposure and, by repeated rewaterings, help maintain temperature and moisture levels in exposed gravels favorable to embryonic development. Darkness will prevent detrimental temperature increases and dehydration of exposed gravel because there are no solar effects. Restricting daily dewatering to darkness, as is usually the case because power demand falls at night, will also be beneficial. This assumes that the spawning areas are close to the dam, and not far enough downstream to remain dewatered during daylight hours.

Overhead sprinkling systems may be used, when extended dewatering cannot be avoided, to cool and maintain moisture levels in exposed gravel beds. Sprinkling may aid the survival of eggs and embryos until hatching. However, sprinkling would have limited effect on the survival of eleutheroembryos and alevins unless significant flow of intergravel water can be maintained. Sprinkling was applied on exposed redds below Lost Creek Dam, Rouge River System, Oregon, in 1977 with some apparent success (Stillwell et al., 1977; Johnson, 1977).

In other situations, particularly during periods of low water in small streams, residual flow may be directed by rock barriers to pass over and into specific areas where redds are located. Similar barriers can be used to completely block residual flow, directing surface water to flow beneath the barrier and pass through the gravel downstream where redds are located.

This method was recently applied on the upper Cle Elum River, Yakima River system, in Washington (Robert Tuck, Yakima Indian Nation, Washington, personal communication, 1983). However, there are no data on effectiveness of flow diversion based on survival and emergence of fry.

The success of any mitigation method applied in field situations should be confirmed by monitoring of the intergravel environment and by follow-up monitoring of alevin survival, fry emergence and outmigration. Site-to-site differences make monitoring a necessity to avoid detrimental conditions. Once the relative success of different mitigation methods are known, refinements can be made for adaptation to site-specific conditions.

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LIST OF FIGURES

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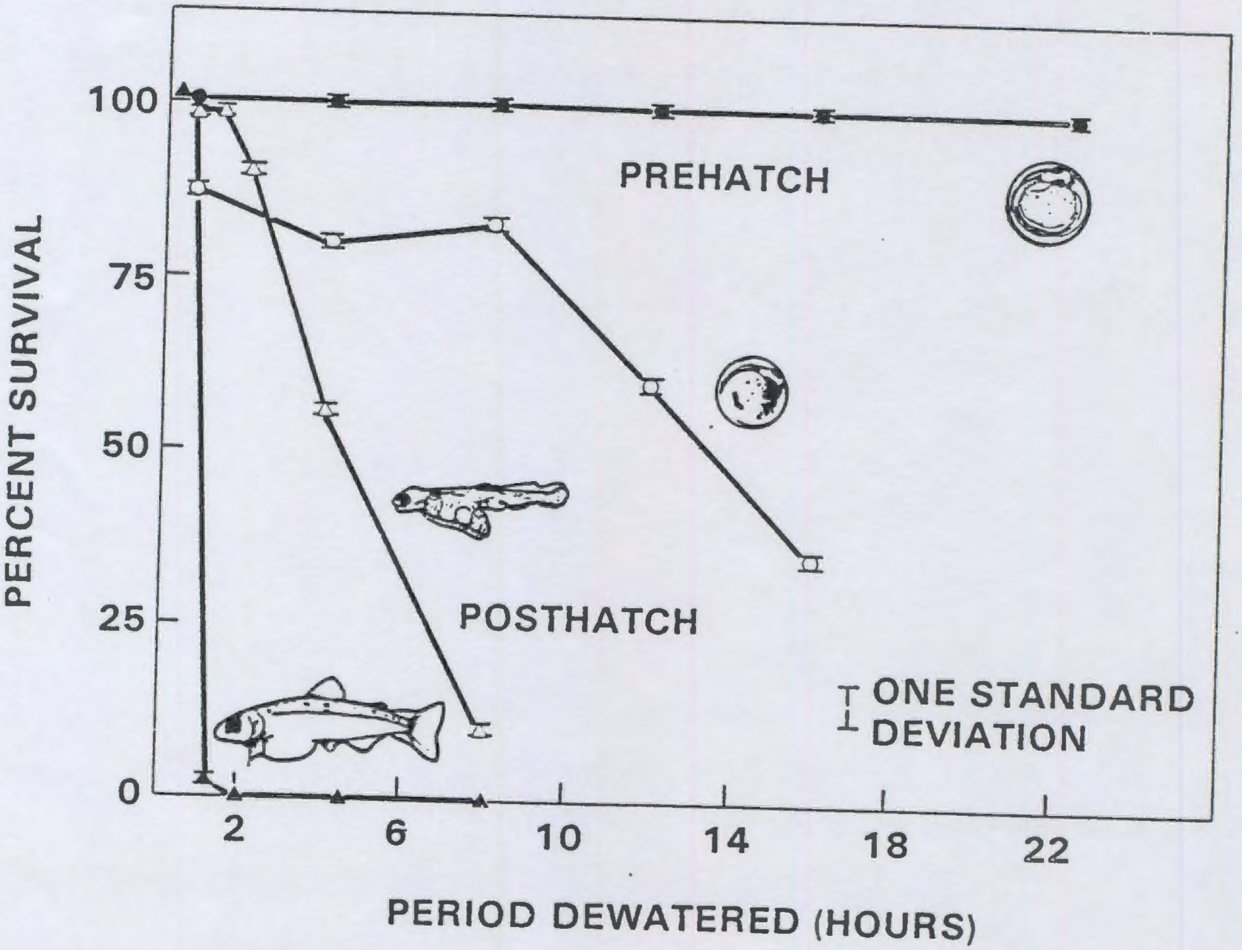

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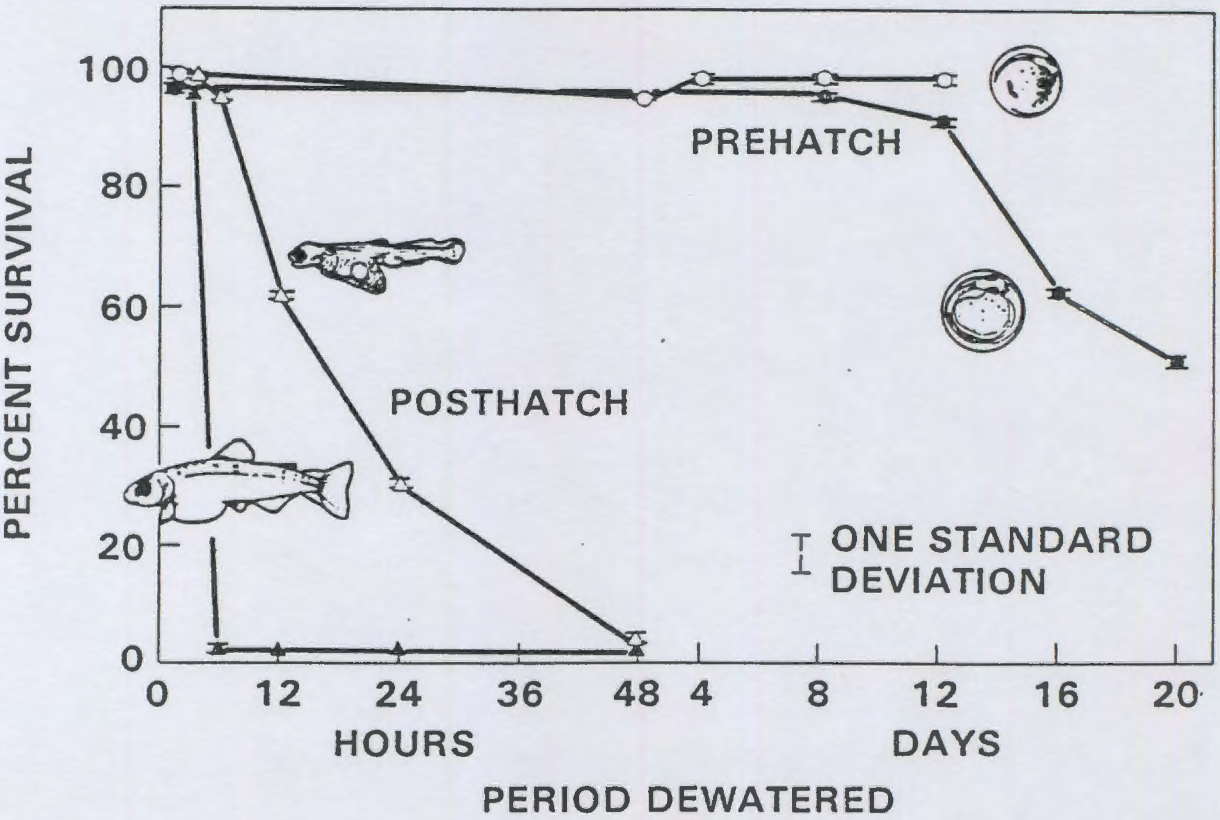

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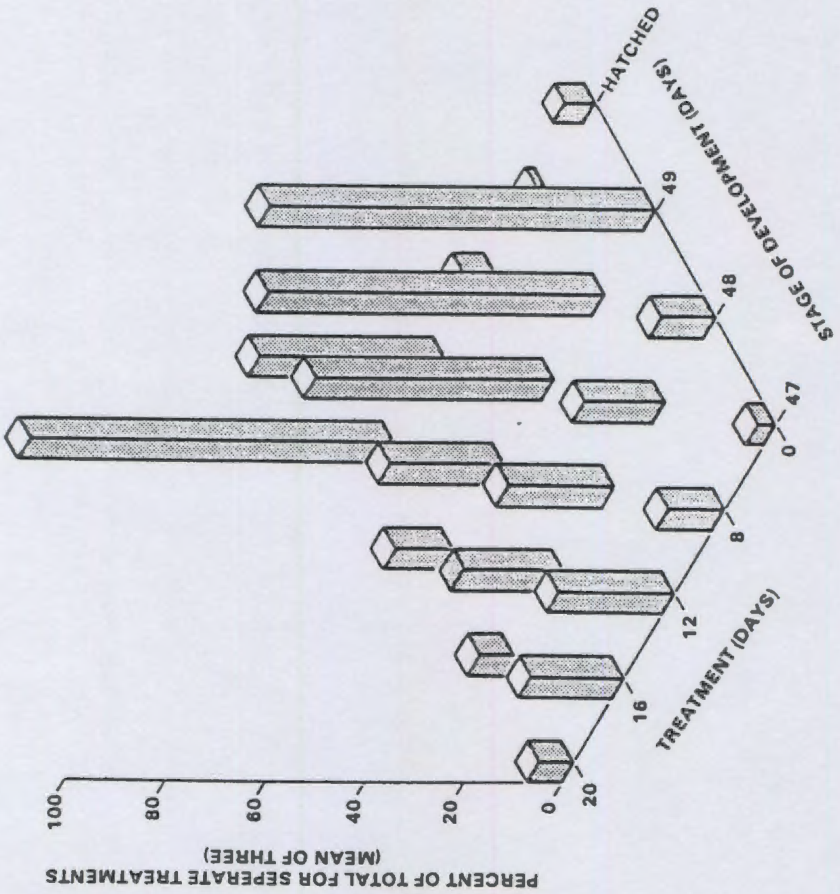

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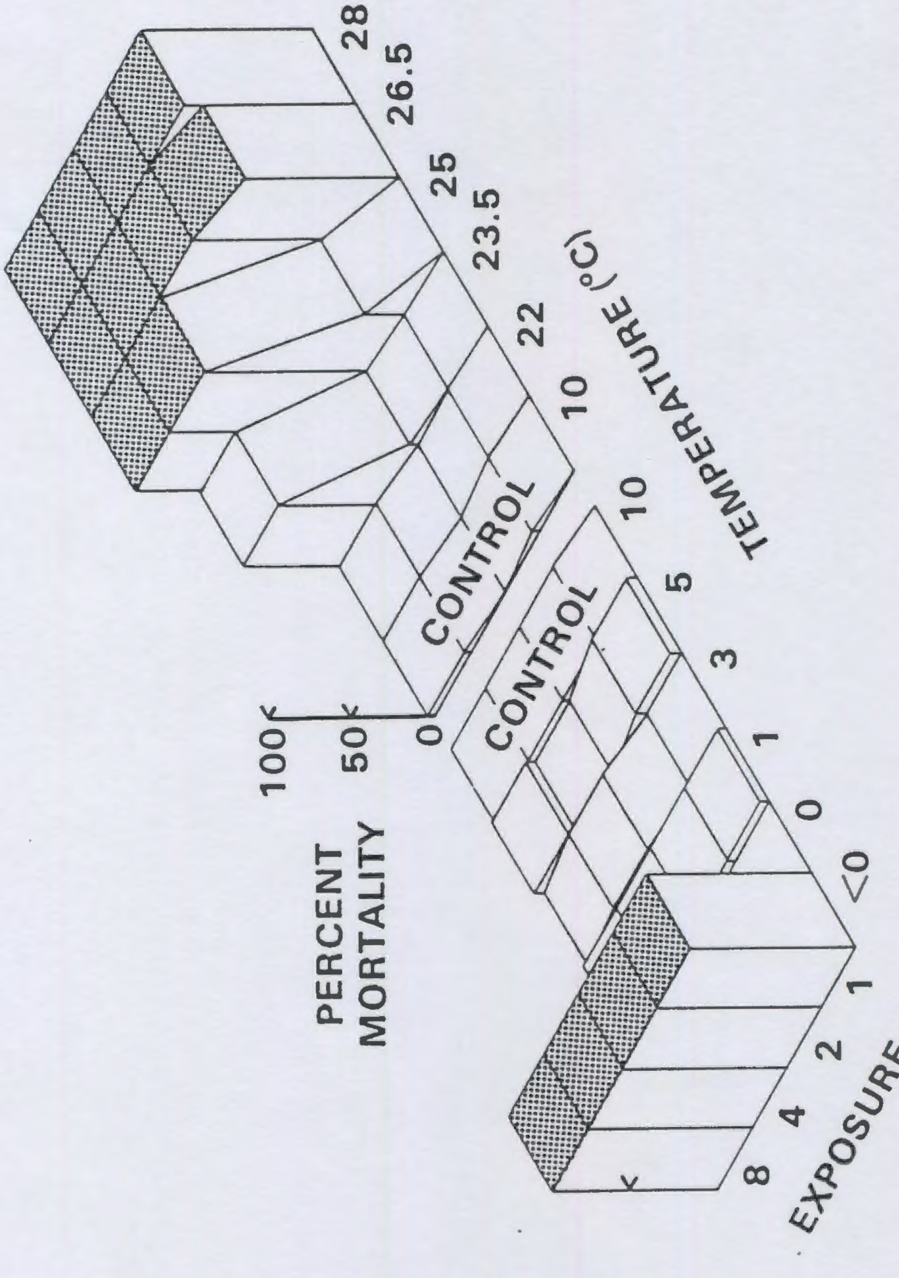

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