Appendix H

Stream Gravel Permeability

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H. STREAM GRAVEL PERMEABILITY

H.1 Introduction

Timber harvest and related forest management practices (e.g., road construction) may increase the delivery of fine sediments to stream channels. Some of these sediments may be deposited in the channel bed, filling pools and infiltrating the bed surface (Moring 1982). Numerous studies have demonstrated that the deposition of fine sediment in spawning riffles reduces reproductive success of anadromous salmonid (Harrison 1923, Hobbs 1937, Wickett 1954, Shelton 1955, McNeil 1966, Cooper 1965, Shelton and Pollock 1966, Philips et al. 1975, Hausle and Coble 1976, Koski 1981, Lotspeich and Everest 1981, Shirazi and Seim 1981, Stowell et al. 1983, Chapman and McLeod 1987, Tappel and Bjornn 1983).

This appendix discusses permeability as a monitoring tool to evaluate the spawning quality of stream gravel. Monitoring permeability in combination with hillslope yields reasonably accurate results about the response of spawning gravel to sediment inputs. For instance, monitoring hillslope identifies sources of sediment input to stream channels. Monitoring gravel permeability assesses changes in the quality of spawning gravel relevant to sediment supply and transport.

H.2 Background[1]

H.2.1 Gravel quality and intra-gravel flow

In all alluvial channels, flow moves both above the bed and through the bed and banks. Surface and sub-surface flow are not distinct but are constantly interchanging. This interchange is driven by hydraulic head and limited by substrate permeability (Darcy 1856, Pollard 1955, McNeil 1966). Hydraulic head (or the slope of the flow) is determined by flow magnitude and channel morphology. Substrate permeability (or the capacity of the substrate to transmit water) is a function of particle compaction, arrangement, and size.[2] Permeability rates increase with decreasing proportion of fine sediment; rates measured by Barnard and McBain (1994) in pea gravel were 59,000 cm/hr. Mixtures with increasing proportions of sand added to the pea gravel showed decreasing permeability rates—from 32,000 cm/hr to 7000 cm/hr. Permeability rates in sand alone were 200 cm/hr.[3]

MRC compared the percent of particles less than 0.85 mm in the bed with the log of permeability and found a significant statistical relationship; however, there was a high amount of variability, as discussed later. Permeability is not only dependent on composition of the gravel, but also the degree of packing of the gravel substrate. Therefore, it is hypothesized that the remaining variability can be explained by the degree of gravel packing (McBain and Trush 2000).

Conditions of intra-gravel flow are often described by “apparent velocity,” which is defined as the rate of seepage through bed material, expressed as the volume of liquid flowing per unit time through a cross section. Because cross sectional area includes both the particles and the voids (pore spaces), apparent velocity is slower than the actual (pore) velocity of water flowing through the voids (Pollard 1955). Apparent velocity is the product of hydraulic head and substrate permeability (Darcy’s law). Spawning redds of anadromous salmonid are usually constructed in

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[1] This background information is primarily from a document developed by Stillwater Sciences and McBain & Trush (1997).

[2] In our HCP/NCCP, permeability is the measurement of a related quantity more properly called *hydraulic conductivity*. The term *permeability* has become standard in the fisheries literature.

[3] Email from S. McBain (McBain & Trush, Arcata, CA) to Sharon Kramer (Stillwater Sciences, Arcata, CA) on December 4, 2006.

channel locations with adequate hydraulic head to drive intragravel flow. In addition, bed topography created by the female's excavation of the spawning redd often enhances intragravel flow. Pyper (1956, as cited in Cooper 1965) used dyes to identify intra-gravel flow paths through a level gravel surface and a surface similar to a new spawning redd; this demonstrated the enhancement of intra-gravel flow caused by the topography of the redd.

Permeability is not uniform at all depths in the gravel profile. Flow through subsurface gravel layers, therefore, is governed by not only the permeability of that layer itself, but also by the permeability of the gravel layers above it (Milhous 1982). Upper layers of relatively impermeable gravel will prevent flow from entering deeper gravel layers, even if these deeper layers are highly permeable.

H.2.2 Gravel quality and survival-to-emergence of anadromous salmonid

Gravel quality is a key factor in the successful incubation and emergence of anadromous salmonid eggs and fry. Researchers have long recognized the relationship between the amount of fine sediment deposited in spawning riffles and successful incubation and emergence (Harrison 1923, Hobbs 1937). Excessive fine sediment in spawning gravel reduces spawning success through two mechanisms: (1) reduction of intra-gravel flow and (2) entombment of emerging fry. The intrusion of fine sediment into gravel interstices reduces intra-gravel flow by reducing gravel permeability (Cooper 1965, Lotspeich and Everest 1981, McNeil 1966, Platts et al. 1979). This results in reduced rates of delivery of oxygen to and removal of metabolic wastes (carbon dioxide and ammonia) from the egg and alevin (Coble 1961, Silver et al. 1963, McNeil 1966, Wickett 1958) (Figure 3). Fine sediments in the gravel interstices can also physically impair the fry's ability to emerge through the gravel layer, trapping (or entombing) them within the gravel (Philips et al. 1975, Hausle and Coble 1976).

H.2.2.1 Literature review

Research on survival-to-emergence of anadromous salmonid has focused primarily on the relationships and interrelationships between oxygen delivery, apparent velocity, permeability, substrate composition, and survival.

Oxygen delivery

Oxygen delivery to the eggs and alevins is a function of dissolved oxygen concentration in the intra-gravel water and apparent velocity (McNeil 1966). Delivery of dissolved oxygen to the egg pocket is the major factor affecting survival-to-emergence that is impacted by the deposition of fines in the spawning substrate. Several studies have correlated reduced dissolved oxygen levels with mortality; impaired or abnormal development; delayed hatching and emergence; and reduced fry size at emergence in sockeye, pink, chum, Chinook salmon, coho salmon, and steelhead trout (Wickett 1954, Alderdice et al. 1958, Coble 1961, Silver et al. 1963, McNeil 1966, Cooper 1965, Shumway et al. 1964, Koski 1981). McNeil (1966) documented egg and larval mortality of 60–90% in pink and chum salmon in association with low dissolved oxygen concentrations during and after the spawning period in 3 southeastern Alaska streams. From dissolved oxygen concentrations measured in redds in a constructed streambed, Koski (1981) noted significant reduction in survival-to-emergence at dissolved oxygen concentration less than 3 mg/L. Shumway et al. (1964) reared coho salmon and steelhead trout from fertilization to hatching in a range of dissolved oxygen concentrations (2.5 - 11.5 mg/L at 10^{o}C) and found that the fry and embryos raised at low-to-intermediate oxygen concentrations hatched later and were smaller at the time of hatching than those raised at near-air saturation levels. Silver et al. (1963) and Cooper (1965) found that low dissolved oxygen concentrations were related to mortality and reduced size in embryos of Chinook salmon and steelhead trout as well as mortality in eggs and larvae of sockeye and pink salmon.

Apparent velocity

Apparent velocity is a key determinant in delivery of dissolved oxygen to an egg pocket. Coble (1961) and Silver et al. (1963) demonstrated that dissolved oxygen concentration is directly related to apparent velocity. In field studies in the Alsea River basin (Oregon), Coble (1961) related apparent velocity to survival-to-emergence in steelhead. He documented a strong correlation between dissolved oxygen concentration and apparent velocity and concluded that oxygen delivery is the major contribution of optimum apparent velocities. Silver et al. (1963) reared steelhead trout and Chinook salmon from fertilization to hatching in different dissolved oxygen concentrations and apparent velocities and found that low dissolved oxygen concentration resulted in mortality; low dissolved oxygen or low apparent velocity resulted in smaller and weaker sac fry. Shumway et al. (1964) reared coho salmon and steelhead trout from fertilization to hatching in a range of dissolved oxygen concentrations (2.5 - 11.5 mg/L at 10^{o}C) and apparent velocities (3 to 750 cm/hr). They found that reduced apparent velocity resulted in reduced size at hatching at all oxygen concentration levels. This effect was nearly as pronounced at high as at low oxygen concentrations, implying that the role of apparent velocity in removing metabolic wastes may limit egg and larval development. Pyper (1956, as cited in Cooper 1965) also found a positive relationship between apparent velocity and survival-to-emergence in sockeye salmon.

Permeability

Several researchers have correlated permeability to the deposition of fine sediment in the gravel substrate and to survival-to-emergence. McNeil (1966) concluded that the resistance to flow caused by the presence of fine particles in the salmon spawning beds governs potential to produce healthy fry. Cooper (1965) showed that fine sediment greatly reduced permeability, resulting in reduced fluid flow and reduced rate of survival-to-emergence in pink and sockeye salmon. Using Cooper's (1965) test flume data, Platts et al. (1979) quantified the relationship between geometric mean diameter and percent fines in the substrate and substrate permeability. Of the two comparisons (percent fines and geometric mean diameter), they found the strongest correlation was with percent fines (<2 mm). The geometric mean diameters of substrates used in this analysis ranged from 13 mm to 69 mm. Percent fines ranged from 0.2 to 7.9. McNeil and Ahnell (1964) also developed a relationship between percent fines (<0.833 mm) and permeability in streams in Alaska.

Few studies have related permeability directly to survival-to-emergence. Wickett (1958) related the percent survival-to-emergence of pink and chum salmon fry to permeability in a controlled flow section of Nile Creek on Vancouver Island, British Columbia. In this study, dead eggs of chum salmon were found in heavily silted parts of the gravel bed where dissolved oxygen concentrations were below the critical concentration for incubation. After silt was removed from the gravel, dissolved oxygen concentration increased to satisfactory levels, which persisted for a year.

Chapman and McLeod (1987) calculated permeability for McCuddin's (1977) survival-to-emergence data for Chinook salmon and developed a significant positive relationship between permeability and survival-to-emergence (although with wide scatter around the regression line). Using Tagart (1984) and Koski (1981) data for natural coho salmon redds, Chapman and McLeod (1987) identified a similar relationship for coho salmon (although, once again, with wide scatter about the regression line). Peter Baker developed a relationship combining Tagart (1984) and

McCuddin's (1977) data.[4] Figure H-1 shows the relationship between survival-to-emergence of Chinook salmon (McCuddin 1977) (+) and coho salmon (Tagart 1976) (o) along with the permeability of the incubation substrate.

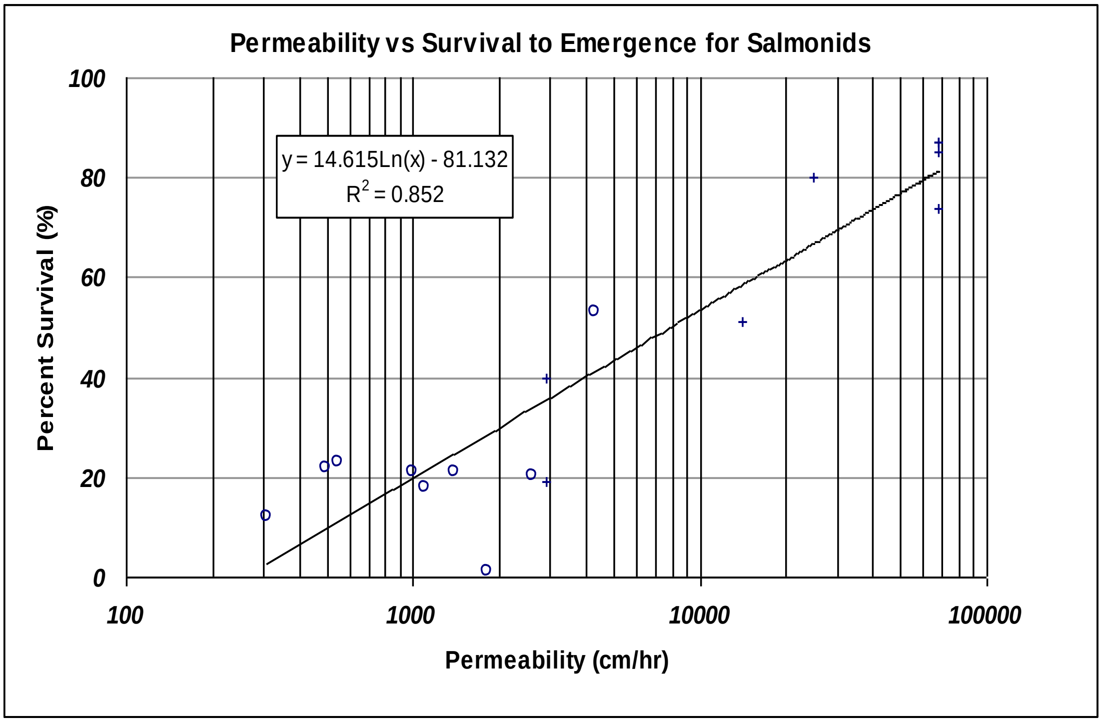

Figure H-1 Permeability vs. Survival-to-Emergence of Chinook Salmon and Coho Salmon

Gravel composition

Many researchers have developed relationships between the amount of fine sediment in spawning gravel and survival-to-emergence. However, the meaning of "fine" sediment has not been standardized; researchers generally have developed correlations based on arbitrary definitions. Cut-offs for fine sediment found in the literature include sediment less than 0.833 mm, 0.85 mm, 1 mm, 2 mm, 3.3 mm, 6 mm, and 6.35 mm (McNeil and Ahnell 1964, Tagart 1976, Lisle and Eads 1991, Koski 1981, Weaver and Fraley 1993, Bjornn et al. 1977, Kondolf et al. 1993).

Several researchers have developed correlations between gravel composition and survival-to-emergence. In Big Beef Creek near Seattle, Washington, Koski (1981) found that a high percentage of sand (<3.3 mm) was positively related to earlier emergence, increased frequency of pre-maturity (i.e., emerged alevin), and reduced survival-to-emergence in chum salmon. Koski (1981) noted that each 1% increase in sand volume reduced survival-to-emergence by 1.26%. Similarly, Shelton and Pollock (1966) sampled substrate composition in the Abernathy incubation channel on a tributary to the Columbia River in Washington where over 70 tons of fine sediment had been deposited in the channel over a two year period. They found that egg survival was inversely related to volume of the gravel interstices occupied by fine sediment. In cutthroat trout, Weaver and Fraley (1993) also found a significant inverse correlation between survival-to-

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[4] Peter Baker (Senior Mathematician, Stillwater Sciences, Berkeley, CA) relayed to Chris Surfleet (MRC) in August 2000 the information about sample sizes necessary to evaluate the effects of permeability on egg survival of coho and steelhead.

emergence and percent fines (< 6.35 mm). In their study, emergence ranged from 70% at 0% fines to 4% at 50% fines. Tappel and Bjornn (1983) related emergence to percentage of particles <0.85 mm and <9.5 mm. These particle sizes exhibited the strongest correlation to emergence.

Sowden and Power (1985) evaluated relationships between dissolved oxygen concentration, apparent velocity, gravel composition, and survival of pre-emergent embryos in a groundwater-fed stream. While they found that survival strongly depended on dissolved oxygen content and apparent velocity, they found no relationship between dissolved oxygen concentration or embryo survival and measures of substrate size. In addition, there was only a limited relationship between apparent velocity and substrate composition. These findings imply that measures of habitat quality based solely on substrate composition may not be suitable for groundwater-fed streams.

Several indices have been developed to describe gravel composition and relate composition to survival-to-emergence. Commonly applied indices include percent fines, geometric mean diameter, and the fredle index. Young et al. (1991) evaluated the performance of 15 gravel composition indices in predicting survival-to-emergence under laboratory conditions and 3 gravel composition indices in evaluating changes in substrate composition caused by spawning activity and by deposition of sediment into former redds. They found that different measures of the geometric mean particle size accounted for the greatest proportion of the variation in survival-to-emergence in laboratory tests. However, the percentage of substrate less than 0.85 mm in diameter best described changes in substrate composition observed in the field. From these results, they concluded that a single measure of substrate composition may be inadequate to both assess potential survival-to-emergence in a substrate and detect changes in substrate composition caused by land use.

Many researchers have related survival to percent fines in the spawning gravel. Tappel and Bjornn (1983) developed a model to predict survival-to-emergence in Chinook salmon and steelhead trout based on the volume of fines <0.85 mm and <9.5 mm. These two points were chosen because they closely approximate the regression of cumulative particle size distribution of particles <25.4 mm. They related the effects of these two groups of particle size on survival-to-emergence in laboratory conditions.

Everest et al. (1981) cautioned against the use of percent fines alone as an indicator of gravel quality or a predictor of potential survival-to-emergence because it ignores the textural composition of remaining particles which can have a mitigating effect on survival. For example, two samples with an average diameter of 10 mm and 25 mm may contain 20% by weight of fine particles <1 mm. However, the pore spaces of the 10-mm sample would be more completely filled with the fine sediment than the 25-mm sample and, therefore, would have a lower permeability. The indices of percent fines do not recognize this difference in gravel structure. Chapman and McLeod (1987) similarly criticized the Tappel-Bjornn method for not accounting for the effects of particles larger than 25.4 mm on the gravel structure.

Platts et al. (1979) and Shirazi and Seim (1981) proposed use of the geometric mean diameter (D_g) as an index of gravel quality. The geometric mean diameter is a measure of the central tendency of the particle sizes comprising the substrate. Shirazi and Seim (1981) calculate the geometric mean as follows:

$$D_g = (D_{84} \text{ x } D_{16})^{1/} \text{ where:}$$

D_g is the geometric mean diameter
D_{84} is the particle size at which 84% of the sample is smaller, and
D_{16} is the particle size at which 16% of the sample is smaller.[5]

Shirazi and Seim (1981) correlated D_g with survival-to-emergence for a combined data set which includes coho salmon, cutthroat, sockeye, and steelhead (Figure H-1).[6] To address species-specific relationships influenced by egg size, they normalized D_g to egg diameter (D_e) and obtained a better fit. However, lumping species which require different particle size distributions for spawning may be inappropriate.

Use of the D_g index has advantages over the use of percent fines in that

- It is a conventional statistical measure used by several disciplines to describe sediment composition.
- It relates to the permeability and porosity of bed sediments and to embryo survival as well as or better than percent fines.
- It is estimated from the total sediment composition (Everest et al. 1981).

However, D_g can be a poor descriptor of gravel quality because gravel containing very different amounts of fine sediment can have the same D_g (Lotspeich and Everest 1981) (Figure H-2).

Lotspeich and Everest (1981) proposed the fredle index (Fr) as an alternative to D_g. This index uses a measure of the ratio of central tendency of the particle size in a sample (D_g) to the dispersion of particle sizes to characterize substrate suitability for spawning salmonids. This index provides a measure of pore size and permeability, both of which increase as the index number increases. However, it was fitted to data from Philips et al. (1975), which included only emergence and did not include egg mortality. Therefore, while the fredle index may be a good descriptor of gravel quality, the preliminary relationship between fredle index and emergence does not represent survival-to-emergence.

Other researchers focused on the emergence stage only (i.e., entombment) and did not address the effects of fine sediment on egg incubation and alevin development. These researchers placed alevins into experimental gravel mixtures and observed their ability to emerge through the gravel. Hausle and Coble (1976) buried brook trout alevins in laboratory troughs containing 0-25% sand (<2 mm) and determined that sand in excess of 20% of the total substrate weight slowed or prevented emergence. Philips et al. (1975) placed coho salmon and steelhead alevins into several gravel mixtures containing 0–70% fine sediment (1-3 mm) and found that coho salmon emergence ranged from 96% in the control mixture to 8 % in the 70% sand mixture. Emergence in steelhead trout ranged from 94% to 18%, respectively.

H.2.3 Effects of timber harvest on gravel quality

Several researchers have documented increased delivery of fine sediment to stream channels after timber harvest and road construction with consequent deposition in spawning gravel (Moring 1982, Shirazi et al. 1981, Stowell et al. 1983). Moring (1982) monitored changes in gravel permeability over 4 years and again at 7 years in 3 Oregon watersheds. One watershed was 82% clear-cut without riparian buffers (Needle Branch); 1 was 25% clear-cut but had 30-m wide riparian buffers (Deer Creek); and 1 was uncut (Flynn Creek). Average permeability in Needle

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[5] Some researchers also use the pair D_{75} and D_{25}.
[6] They combined survival-to-emergence data with the emergence-only data of Philips et al. (1975).

Branch decreased markedly after the basin was clear-cut, dropping from a pre-harvest average of 4900 cm/hr to an average of 1100 cm/hr in the first year after harvest. Average permeability then remained relatively constant but depressed relative to initial conditions at 2400 cm/hr over the next 6 years. Average permeability in Flynn Creek and Deer Creek remained fairly stable throughout the study.

Similarly, Cederholm et al. (1981) documented increased sediment yields and reduced survival-to-emergence in coho salmon in watersheds with extensive logging roads in Clearwater Creek in the Olympic Mountains, Washington. These researchers found that significant amounts of fine sediment (< 0.85 mm diameter) were delivered from tributary basins with many roads. The highest accumulation of fine sediment in stream channels occurred in basins where road area exceeded 2.5% of the basin. Road density of 2.5 km/km^2 produced sediment at 2.6 to 4.3 times the natural rate for the drainage basin. The increased sediment was correlated with reduced survival-to-emergence when the percentage of fines exceeded natural levels. There was a rapid decrease in survival-to-emergence with each 1% increase in the volume of fine sediment above natural levels.

H.2.4 Selection of parameters to monitor

Monitoring the effects of increased sediment delivery to stream channels caused by timber harvest can be accomplished through several methods. The preferred method would

- Monitor sediment-related factors known to directly affect spawning success of anadromous salmonid.
- Monitor factors directly related to increased sediment delivery.
- Be cost-effective and time-effective.

Dissolved oxygen delivery, apparent velocity, gravel permeability, and gravel composition are all sediment-related factors known to affect spawning success of anadromous salmonid. However, many of these factors are difficult to directly relate to increased sediment delivery because they are also affected by other variables (such as hydraulic head or water temperature). Others are difficult to measure due to cost or lack of technology. Of these variables, only permeability can be directly related to increased sediment delivery and measured effectively in cost and time.

H.2.4.1 Dissolved oxygen

Dissolved oxygen is the key parameter governing survival-to-emergence. Dissolved oxygen can be measured quickly and accurately using a standpipe and dissolved oxygen meter. It can be, therefore, a useful monitoring parameter. However, dissolved oxygen is affected by a number of variables not directly related to fine sediments, including streamflow magnitude, temperature, and biological oxygen demand. Dissolved oxygen concentration cannot be directly related only to increased sediment delivery; it is not a sufficient monitoring parameter to detect the impacts of fine sediment resulting from timber harvest or related management actions.

H.2.4.2 Apparent velocity

Coble (1961), Silver et al. (1963), and Milhous (1982) all related apparent velocity to survival-to-emergence. However, because apparent velocity is a function of permeability and hydraulic head, it is not a direct measure of the effects timber harvest and forest management which, although they may affect permeability, would not affect hydraulic head. Apparent velocity, therefore, is confounded by flow magnitude (hydraulic head), which can result in changes in apparent velocity without any change in gravel permeability.

In addition, accurate and precise measurement of apparent velocity is difficult to obtain in the field. Apparent velocity can be measured directly by meters (Blanchfield and Ridgeway 1996) or through dye dilution or ion adsorption techniques (Terhune 1958, Clayton et al. 1996), or it can be calculated from measurements of flow length, hydraulic head, and permeability (Milhous 1982). Meters provide the quickest measurements; however, these instruments are costly. Moreover, they do not measure apparent velocity over a sufficient range to describe conditions in gravel substrates. Grost et al. (1991) demonstrated that the dye dilution technique is not sufficiently precise to provide a good assessment of apparent velocity. While apparent velocity can be calculated as a function of hydraulic head, hydraulic head over the short horizontal distance of a redd is difficult to accurately measure. It requires the installation of a piezometer at the upstream and downstream end. Grost et al. (1989) concluded that mini-piezometers yield poor apparent velocity estimates.

H.2.4.3 Gravel composition

Gravel composition has been extensively correlated to survival-to-emergence in the laboratory and to some extent in the field. Several indices of gravel composition (D_g, the fredle index, the Tappel-Bjornn index and other indices of percent fines) have been developed. Assessment of gravel composition directly describes changes in fine sediment deposition in the spawning substrates over time, which is a potential impact of timber harvest. However, this measure only indirectly describes the potential impact to salmonids (reduced gravel permeability and intra-gravel flow). In addition, quantitative sampling and analysis of gravel composition are labor intensive and, therefore, expensive. They require as much as 6 hours for a 2-person crew to obtain and process one sample. Complete sampling, processing, and data analysis can require several months. Further, the amount of variability in gravel composition samples requires a high number of samples to accurately predict results. In the Garcia River, McBain and Trush (2000) found that it would require 37 samples to accurately categorize the percent of fine sediment in a stream reach within 2% and 148 samples within 1%. This kind of sampling is highly intrusive, and, therefore, inappropriate for monitoring conditions during the spawning and incubation seasons.

H.2.4.4 Permeability

Gravel permeability and gravel composition are most directly related to fine sediment accumulation in the spawning riffles. Permeability is a property of the gravel itself, independent of streamflow conditions or bed slope. Dissolved oxygen delivery and apparent velocity, on the other hand, are affected by factors not necessarily related to sediment accumulation, such as water temperature, biological oxygen demand, and flow magnitude. Gravel composition and permeability, therefore, are the best parameters to assess gravel quality.

Permeability is a more direct measure, however, of the quality of the incubation environment, whereas gravel composition provides only an indirect measure of flow and oxygen delivery conditions in the redd. Gravel quality indices, such as percent fines, geometric mean, and the Fredle index are the most common independent variables related to egg-to-fry emergence success (e.g., Phillips et al. 1975, Tappel and Bjornn 1983). This approach assumes that as percent fine sediment increases, intra-gravel water flow decreases, oxygen supply decreases, metabolic waste removal decreases, and fry access to the water column decreases. A preferable approach would be one that bypasses the indirect measure of gravel quality and measures the variables directly affecting egg survival. Chapman and McLeod (1987), in their development of fine sediment criteria in the Rocky Mountain region, identified permeability as a useful tool for correlating fine sediment with survival as well as assessing the intrusion of fines into the gravel substrate.

Gravel permeability can be measured in the field rapidly and cost-effectively, at perhaps 10% of the cost of bulk sampling, using a standpipe (Terhune 1958, Barnard and McBain 1994 2000). The ease and rapidity of standpipe sampling makes permeability a simple, inexpensive, and accurate measure of gravel quality, thereby allowing the assessment of a much larger area at less cost than traditional bulk sampling methods. Unlike assessment of gravel composition, permeability measurements require no laboratory analysis or processing. Young et al. (1991) reported wide variation among measurements from different technicians, but their measurements were only taken for 5 to 10 seconds and used a handheld pump, not an electronic pump as MRC uses. Furthermore, permeability measurements are not as intrusive as other monitoring methods causing little disturbance to the stream substrate.

In summary, permeability is the only descriptor of gravel quality that

- Is known to directly affect spawning success of anadromous salmonid.
- Is directly related to increased sediment delivery.
- Can be measured effectively in terms of cost and time.

As such, the assessment of substrate permeability provides a powerful tool for monitoring the effects of increased sediment delivery on spawning and incubation conditions of anadromous salmonid.

H.3 Development of a Permeability Monitoring Protocol for MRC

MRC will be using permeability observations within stream monitoring segments. To determine the adequate number of samples to characterize the spawning gravel within a stream segment, MRC performed a power analysis based on observations we made across the plan area. Our science staff took the permeability measurements in the pool tail-out or riffle crest, the location where the majority of anadromous salmonid spawning occurs within the plan area.

H.3.1 Determining adequate sample size

Peter Baker, a biologist and statistician with Stillwater Sciences (Berkeley, CA), developed a simple predictive model of survival-to-emergence from the limited data available in the literature. This model is based on the data of Tagart (1976) and McCuddin (1977). Tagart (1976) evaluated survival-to-emergence for coho salmon by trapping 19 natural redds over 2 seasons in 8 tributaries of the Clearwater River, Washington. McCuddin (1977) examined survival-to-emergence in Chinook salmon and steelhead in artificial redds constructed in experimental troughs. The model fitted to this data is shown in Figure H-2. The fitted model was:

$$\text{Survival} = -0.82530 + 0.14882 * \mathit{ln}\ \text{Permeability}\ (r^2 = 0.85,\ p<10^{-7}).$$

The number of samples required is based on the desired power to detect changes in permeability or predicted survival-to-emergence. Measurements were conducted in several coastal drainages in Mendocino County, CA. Permeability was measured in 4 randomly selected pool tail-outs of a stream monitoring segment. At each pool tail-out 3 permeability measurements were taken, with 3 measurements positioned at the ¼, ½ and ¾ mark of the wetted channel. The permeability measurements were taken at a depth of 25 cm. A total of 261 permeability measurements were taken. Table H-1 shows the distribution of these permeability observations for determination of adequate sample numbers.

Table H-1 Distribution of Permeability Observations

Drainage Basin	Number of Monitoring Segments	Total Number of Permeability Samples
Albion River	4	45
Navarro River	8	87
Elk Creek	2	27
Noyo River	6	57
Hollow Tree Creek	5	45

To determine the number of samples needed to adequately detect differences in permeabilities within and among pool tail-outs, Peter Baker conducted power analyses using the simple predictive model constructed from the Tagart (1976) and McCuddin (1977) data. The power analysis was designed to determine the number of samples needed to adequately detect differences in permeabilities between sites, or changes in permeability over time using 2-sample homoscedastic t-tests. The analysis was based on the assumption that sample *ln* permeabilities within a riffle or tailout unit were normally distributed, and that the distributions for different riffles and facies[7] units have the same variance. That is, the model was:

$$\mathit{ln}\ \text{permeability} \sim N(m_r, \sigma).$$

In this equation, m_r is the mean *ln* permeability of the riffle/facies unit from which the sample is drawn and σ is the common standard deviation. Conventional criteria of 95% confidence and 80% power and minimum detectable differences in survival-to-emergence of 10%, 20%, and 40% were selected for the power analysis. The number of permeability observations needed for the power analysis relative to the percent of detectable survival-to-emergence are 101 (10%), 26 (20%), and 7 (40%). MRC has chosen as its threshold of concern 20% change in survival-to emergence. Therefore, we will need to take at least 26 samples per stream segment. The estimated permeability at the 20% survival-to-emergence level is approximately 1000 cm/hr (see Figure H-1). Thus, 26 samples per stream segment should allow for estimates of permeability within ±1000 cm/hr, which is 10% of the MRC instream objective for permeability of 10,000 cm/hr.

H.3.2 Location of permeability measurements in the stream segment

It has been determined that 26 permeability measurements will reliably detect a 20% change in the survival-to-emergence for salmonids. The locations of these permeability measurements need to represent the conditions within the stream channel segment. One option is to place permeability measurements at locations where salmonids have spawned previously. This provides information on permeability where salmonids spawn. However, it is not a good indication of stream gravel response to increased sediment inputs. This is because spawning salmon are somewhat selective where they spawn, choosing best substrate and channel locations. Also, the spawning salmonids clean and modify the gravel where they create redds influencing the permeability observations.

To adequately assess instream sediments influences on stream gravel quality for spawning, one should distribute the permeability observations throughout the stream segment, at locations where there is gravel suitable for spawning, but randomly select the locations so that observations are not biased. The location where the majority of spawning gravel is found and the majority of

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[7] Facies units are any morphological unit of a stream (e.g., pool, riffle, run, glide).

spawning occurs for coho salmon and steelhead trout is in the pool tail-outs. The monitoring segments MRC will use for permeability observations are approximately 20-30 channel widths in length. This typically corresponds with 5-10 pool tail-outs. By taking a similar number of permeability observations in each pool tail-out across the monitoring segment, we will not bias the permeability observations. In each individual pool tail-out, we will randomly select the location of the permeability measurement to ensure that our observations are not biased toward higher or lower quality gravels within the pool tail-out. This method, in small watercourses, could result in some samples which are not independent.

H.3.3 Site readings to represent permeability

When a permeability measurement is taken at a spot (or site) in the stream, the first few permeability readings typically are lower than the later readings. We attribute this to flushing of fine sediment or organic particles in the streambed in close proximity to the stand pipe. This is supported by the fact that water brought up during the initial permeability readings typically is muddy and clears as subsequent readings are taken. The number of permeability readings to represent a particular site has not been standardized but flushing of the finest particles close to the standpipe should be considered.

A common technique for readings of permeability at a site is to take permeability readings until they reach an observed asymptote or no longer increase in value. Depending on the location, this typically takes 3-8 readings. MRC has observed an average of between 4-5 observations from our data collection efforts. Another technique is to take 1 reading and consider it representative of the site. Both techniques have their advantages and disadvantages. We have chosen a technique that provides a mix of the 2 techniques, taking 5 measurements and using the median reading as the representative permeability of the site. Taking only 1 reading may not capture the variability of permeability at a site. Taking readings until permeability values no longer increase or reach an asymptote can be subjective. By taking 5 observations then stopping, we capture the variability of readings and the initial increase in readings without any subjectivity in the number of readings.

H.3.4 Permeability monitoring protocol

To determine stream gravel quality, MRC will measure gravel permeability within pool tail-outs of the long term channel monitoring reaches, using a 1 in. diameter stand-pipe and an electric pump to create the water suction. We will take 26 permeability measurements in each monitoring segment at a depth of 25 cm. This is the maximum depth at which coho salmon and steelhead spawn. The measurements will be evenly distributed among all pool tail-outs in the segments, with any additional measurements taken in tail-outs behind the deepest pools. The measurement location in each tail-out will be randomly selected from a 12-point grid (3 points wide and 4 points long) in the tail-out.

At each measurement location, 5 permeability repetitions will be taken with the median of these observations representing the permeability of the measurement location. To characterize the entire monitoring segment, we will use the geometric mean of the 26 median permeability measurements and determine the natural log (see H.3.1):

$$\text{Survival} = -0.82530 + 0.14882 * \ln \text{permeability}$$

It is important to emphasize that the use of this survival relationship is only an index of spawning gravel quality in the segment. The permeability measurements are taken randomly in pool tail-outs and are not indicative of where a salmon may select to spawn. Therefore, the survival percentage developed is only indicative of the quality of potential spawning habitat and not as an absolute number.

H.4 Fine sediment Composition and Stream Gravel Permeability

Permeability was compared to substrate composition from data collected in coastal drainages of Mendocino County, CA during the summers of 1998 and 1999. In addition, at each pool tail-out sampled for permeability, one bulk gravel sample was collected at the permeability measurement site closest to the thalweg of the channel, yielding 85 bulk samples that could be related to permeability. Bulk samples were taken using a 12 in. diameter steel cylinder as described in Platts et al. (1983). The cylinder was centered over the location of the permeability measurement and driven into the bed to a depth of 30 cm. For the comparison, only the substrate from the 18–30 cm depth was used. All samples were dried, sieved (using 50, 25, 12.5, 6.3, 4.75, 2.36, and 0.85 mm sieves), and weighed, with the resulting percentage by weight of each size class determined. Particles larger than 50 mm were not included in the particle distribution, as we were concerned with the distribution of small-sized particles.

Table H-2 Distribution of Permeability and Bulk Gravel Samples

Drainage Basin	Number of Monitoring Segments	Total Number of Permeability Samples	Total Number of Bulk Samples
Albion River	4	45	16
Navarro River	8	87	30
Elk Creek	2	27	6
Noyo River	6	57	18
Hollow Tree Creek	5	45	15

From this data-set, the relationship between permeability and percent of size class particles was examined. The best relationship was found between the log of permeability and percent of particles less than 0.85 mm. This relationship was found to be statistically significant; however, a high amount of variability is not explained by the relationship ($r^2 = 0.278$). McBain and Trush (2000) made similar observations in the Garcia River. They found that the percent of particles <0.85 mm provided the best correlation with permeability ($r^2 = 0.25$). Another study by Graham Matthews and Associates (2001) along the Trinity River found a similar relationship with the percent <0.85 mm particles ($r^2 = 0.35$).

The McBain and Trush (2000) study found that the relationship improved when 2 size classes, 32 mm and 0.5 mm, were used in a multiple regression ($r^2 = 0.45$). However, the MRC data-set did not show this improved correlation between 2 size classes. Another study by Graham Matthews and Associates did not test 2 size classes. They found that when the mean permeability for multiple sites and observations were compared to the percent <0.85 mm particles, the relationship improved significantly ($r^2 = 0.77$). However, when 2 samples were removed that had a high proportion of large grain materials, the relationship between permeability and percent of particles <0.85 mm became stronger ($r^2 = 0.98$). These observations suggest that the frame work of gravel sizes in the matrix is a strong determinate for permeability, but the proportion of fine particles in the matrix is a statistically significant predictor (with high variability) of permeability.

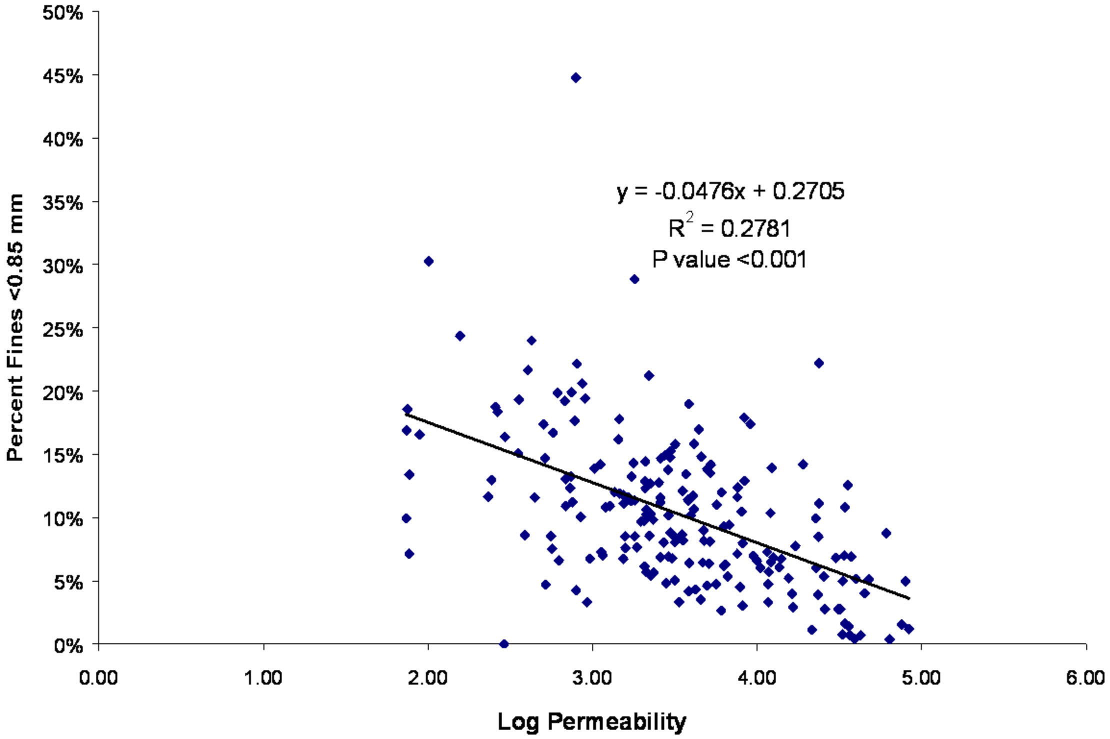


Figure H-2 Log Permeability vs. Percent Particles <0.85 Millimeters

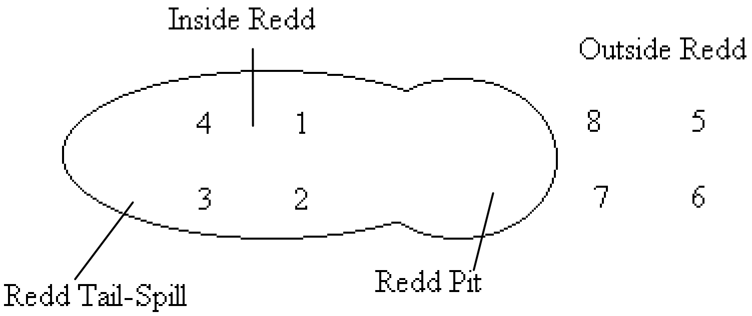
H.5 Effects of Anadromous Salmonid Redds on Permeability

To attempt to determine the difference in permeability between stream gravels that have been built into a redd by spawning salmonids versus non-redd areas, MRC analyzed 2 separate field trials. The first data-set was collected in 1997 on the mainstem and select tributaries of the Garcia River (Stillwater Sciences and McBain & Trush 1997). The second data-set was collected in 1999 on mainstems and select tributaries of the Albion River and the North Fork Navarro River (MRC 1999).

The permeability measurements were taken using the equipment and methods outlined in Barnard and McBain (1994). A 1.5 in. diameter standpipe was used to make the permeability measurements for the Garcia River data-set and 1 in. diameter standpipe was used to make the permeability measurements for the Albion and North Fork Navarro Rivers data-set. For the Garcia River data-set, a hand pump was used to create the appropriate pressure head in the standpipe while the Albion and North Fork Navarro Rivers data-set used an electric pump.

For the Garcia River data-set, permeability measurements were taken during low-flow conditions at identified redd sites following hatching of anadromous salmonid eggs (in this case during the summer season). The standpipe was driven into the gravels 25 cm below the streambed surface. Each time the standpipe was inserted into the gravels, researchers took 4 separate permeability measurements . This was repeated 4 times both inside and outside the redd (Figure H-3). The mean of the permeability measurements inside the redd and outside the redd (non-redd) were reported as permeability values for the respective sites.

Figure H-3 Sampling Locations for Permeability and Bulk Gravel Samples



1 - Permeability measurement

A total of 15 redd sites and 15 non-redd sites were sampled. Of these sites, 3 of the redd and non-redd sites were excluded from the analysis. The 3 sites excluded were all located in the same tributary of the Garcia River, Mill Creek. The sites were excluded due to poor substrate conditions (i.e., angular rocks suggesting substrate that had been deposited from streamside sources rather than fluvial sources) and lack of defined pool tail-outs, making it difficult for the sampling protocol to be followed.

The Albion River and North Fork Navarro River permeability samples were taken when streamflow was low enough for personnel to safely sample permeability following hatching of anadromous salmonid eggs (in this case May). Identified redds had 2 permeability measurements taken in the redd tail-out at a depth of 25 cm, with the mean of the 2 permeability readings used to characterize the redd. To characterize the non-redd permeability, researchers took 3 measurements across the pool tail-out in which the redd was located (in an area assumed not influenced by redd development) at a depth of 25 cm. The mean of 3 non-redd permeability measurements was used to characterize the non-redd permeability. A total of 9 redd sites and 9 non-redd sites were sampled in the Albion and North Fork Navarro Rivers.

Figures H-4, H-5, and H-6 show a plot of the Garcia River data set and the Albion and North Fork Navarro River data set. Linear regression indicates a strong relationship between redd and non-redd ln permeability. The ln permeability of redd sites are observed to be 2.6% more permeable than the non-redd sites in the Garcia River data-set ($r^2 = 0.4857$, $p<0.0001$) The ln permeability of redds are observed to be 3.3% more permeable than the non-redd ln permeability measurements in the Albion and North Fork Navarro River data set ($r^2 = 0.62$, $p<0.0001$).

Figure H-4 Redd vs. Non-Redd Permeability for the Garcia River, 1997

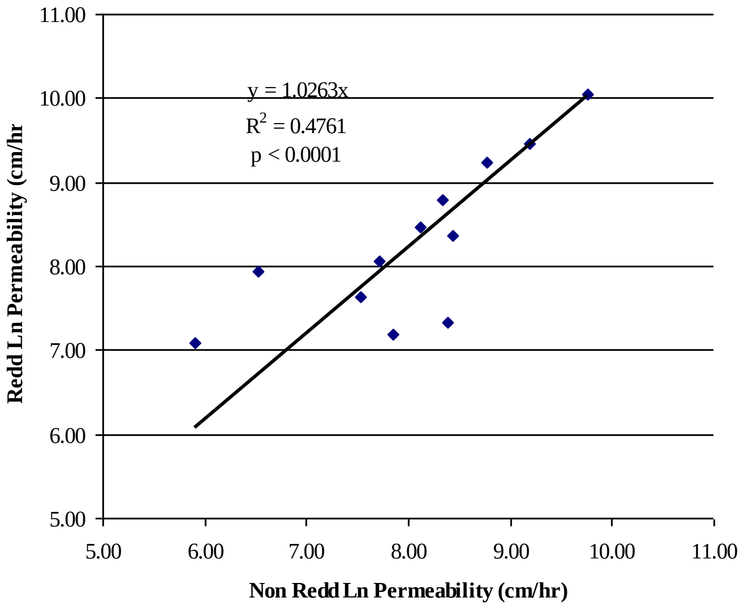
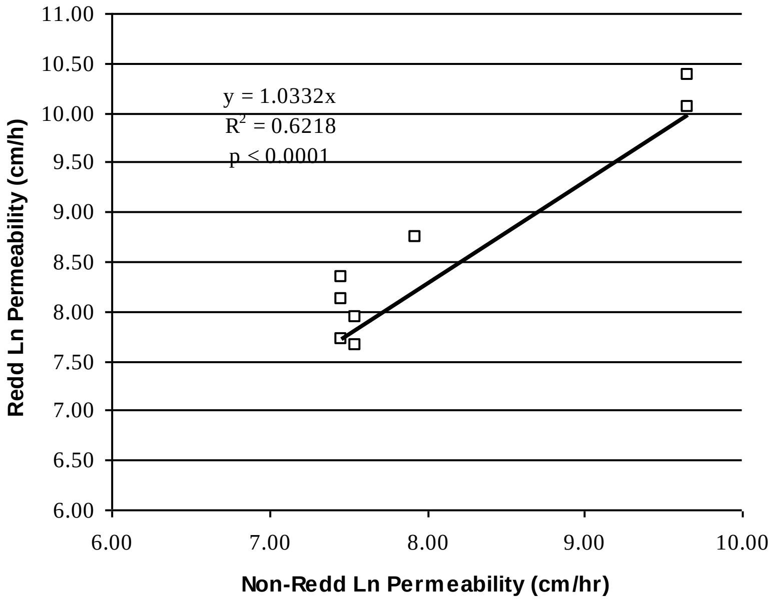
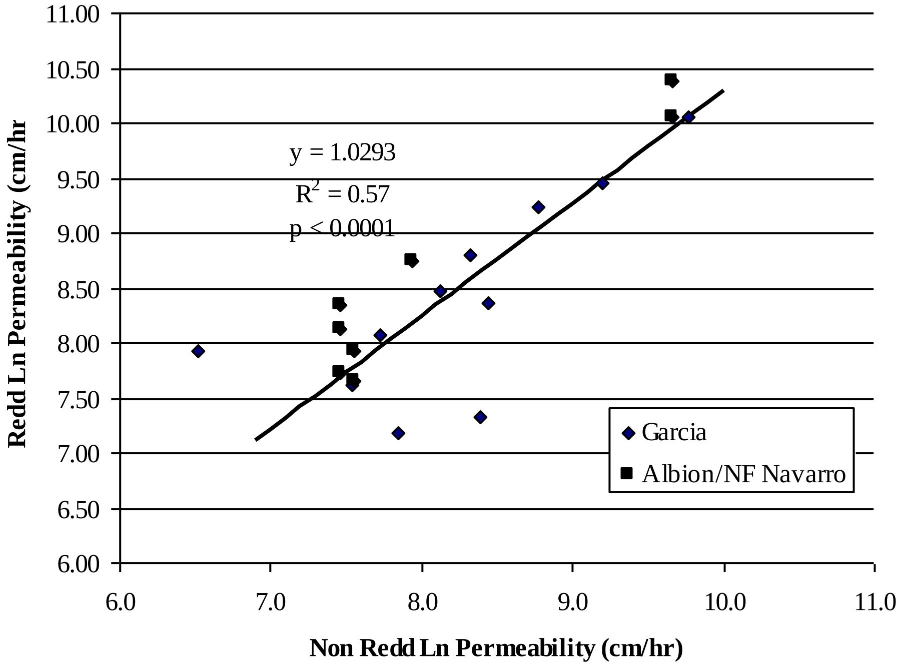


Figure H-5 Redd vs. Non-Redd Ln Permeability for the Albion and North Fork Navarro



When the Garcia River and Albion/North Fork Navarro Rivers data-sets for redd vs. non-redd permeability are combined, similar results are observed. The combined data-sets show a significant relationship between the ln of permeability in redd sites compared to non-redd sites, with redd sites having higher values (Figure H-6)($r^2 = 0.57$, $p<0.0001$).

Figure H-6 Redd vs. Non-Redd Ln Permeability - Garcia, Albion, and N. Fork Navarro



Redd sites were observed to be more permeable than stream substrate adjacent to redds (i.e., non-redd sites). This is an expected response to redd construction of anadromous salmonid. When a redd is constructed, fine particles are cleaned from the site creating a more porous and thus permeable substrate (Kondolf et al. 1993). Furthermore, the shape and location of a redd can create hydraulic conditions conducive to increased permeability (Pyper 1956, as cited in Cooper 1965).

The Garcia River and Albion/North Fork Navarro River data sets showed similar relationships. Both had significant relationships for stream substrate permeability between the ln of permeability for redds and non-redds, with redd sites being more permeable than non-redd sites. The Albion/North Fork Navarro data set showed a higher percentage difference (77%) for redd to non-redd permeability (using actual values not ln) than the Garcia River data-set which showed a 30% increase. Collectively,[8] the redd versus non-redd data showed redd permeability 53% greater than non-redd permeability. Based on this information and the assumption that salmonids choose the best habitat for spawning, MRC selects all potential spawning areas in a monitoring reach and samples within the tailouts of these pools to obtain the most accurate estimate of potential spawning habitat.

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[8] Garcia, Albion, and North Fork Navarro data