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Modeling embryo survival affected by sediment deposition into salmonid spawning gravels: Application to flushing flow prescriptions

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Abstract. This paper presents a framework for predicting embryo survival in salmonid spawning gravels as a function of sediment deposition. This framework integrates three quantitative relationships modeling the variations of substrate permeability with sediment deposition, apparent velocity with substrate permeability, and embryo survival rate with apparent velocity. The model allows evaluation of the impacts of sediment deposition on embryo survival. The relative sensitivity of embryo survival to three selected environmental factors is investigated. The model results indicate that embryo survival is most sensitive to the composition of fine sediments (or sediment-gravel size ratio). The maximum influences of the hydraulic pressure head and the length of intragravel flow path are ~60 and 35% of the value influenced by size ratio. The proposed model is applied to determine the timing of flushing flows. The results suggest that the interval between flushing flows should be reduced when higher levels of embryo survival are prescribed or higher near-bed sediment concentrations are imposed.

1. Introduction

Salmonids (salmon and trout) use the river gravel beds as incubation habitat. Natural gravel bed streams are typically characterized by pool-riffle sequences that provide considerable variations in water depth and flow velocity. Salmonids explore suitable locations for spawning (usually at the head of the fast-flowing riffle), where the female excavates a pit and releases fertilized eggs into the bottom [*Burner*, 1951; *Hawke*, 1978; *Chapman*, 1988]. After spawning, the female resumes digging upstream to bury the area of egg deposition (the so-called "egg pocket"). The embryos are therein protected against bed load motion and scour during high flows. The typical morphology of the resultant nest (or redd) right after spawning, with a pit upstream and a tailspill downstream, is shown in Figure 1. The hydrodynamics induced by the topographic form promotes a downwelling flow into redd. The favorable pressure gradient exerted between the upstream and downstream faces of the tailspill forces streamwater to flow into and through the substrate. Such flow phenomena have been observed with dye, in both the field [e.g., *Hobbs*, 1937; *Burner*, 1951; *Stuart*, 1953] and laboratory [e.g., *Cooper*, 1965; *Harrison and Clayton*, 1970; *Thibodeaux and Boyle*, 1987]. This type of flow benefits the exchange of dissolved oxygen and removal of metabolic waste to maintain an intragravel environment crucial for embryo survival [*Coble*, 1961; *Vaux*, 1962; *Chevalier et al*., 1984]. The initial winnowing of fine sediment by the female during redd construction further enhances the permeability of gravel and the interstitial flow [*McNeil and Ahnell*, 1964; *Kondolf et al*., 1993]. Redd topography is planed off by flows large enough to transport significant quantities of bed load [*Lisle and Lewis*, 1992]. Nevertheless, flow downwelling is in many instances induced by pressure gradients over pool tails, rock outcrops, boulders, or woody debris.

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Natural and anthropogenic environmental changes can degrade the quality of incubation habitat. Among the factors that could adversely affect embryo survival, intrusion and accumulation of fine sediment into the gravel substrate is regarded as one of the most detrimental [*Koski*, 1966; *Shirazi and Seim*, 1981; *Sear*, 1993]. Fisheries researchers generally agree that fine sediment intrusion into spawning gravels can significantly reduce substrate permeability and intragravel water velocities, thereby restricting the supply of oxygenated water to developing salmonid embryos and the removal of their metabolic wastes. Excessive fine sediment deposition can effectively smother incubating eggs and entomb alevins [e.g., *Vaux*, 1968; *Phillips et al*., 1975; *Iwamoto et al*., 1978]. *Chapman* [1988] provided a comprehensive review of a large body of literature dealing with the effects of fines on incubating embryos. In summary, previous investigators have demonstrated that juvenile salmonid survival correlates positively with the dissolved oxygen and the apparent velocity of intragravel flow moving past the embryos [e.g., *Alderdice et al*., 1958; *Silver et al*., 1963; *Shumway et al*., 1964; *Cooper*, 1965; *Davis*, 1975]. They have also shown that survival rate is positively related to the permeability and grain size of the gravel substrate yet negatively related to the fines content [e.g., *Wickett*, 1958; *Wells and McNeil*, 1970; *Koski*, 1975; *Shirazi et al*., 1981; *Cederholm et al*., 1981; *Tappel and Bjornn*, 1983].

Most previous observations were based on single-factor analyses [*Chapman*, 1988]. In the predictive relationships developed from those investigations, embryo survival is mainly linked to a single factor (such as dissolved oxygen, apparent velocity, permeability, size of gravel, or fines content). However, the incubation environment is a complex system involving multiple factors that simultaneously act to influence outcomes. Moreover, a number of factors other than those considered above, such as the size of fine sediment, porosity of framework

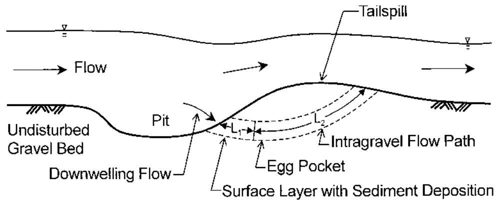

Figure 1. Typical morphology of spawning redd and sketch of intragravel flow. (L_1 is the length of flow path through the sand seal in the surface layer; L_2 is the length of flow path through the surrounding gravels; $L_1 + L_2$ is the total length of the intragravel flow path.)

and matrix materials, hydraulic gradient of intragravel flow, redd dimensions, and the species concerned must affect embryo survival. For example, *Tappel and Bjornn* [1983] pointed out that Chinook salmon (*Oncorhynchus tshawytscha*) survival varied widely (from 20 to 80%) at a given content of fines (10% by volume), depending upon the size distribution of the fine sediment. *Peterson and Metcalfe* [1981] found that fine sand (0.06–0.5 mm) reduced embryo survival of Atlantic salmon (*Salmo salar*) more effectively than coarse sand (0.5–2.2 mm). *Chapman* [1988] used the data of *Koski* [1966] to demonstrate large differences in embryo survival (up to an 80% difference) for a single given gravel permeability. All of these facts indicate that the application of single-factor relationships for survival rate assessment is inappropriate. *Lisle and Lewis* [1992] pointed out that for simulating the effects of sediment transport on survival of salomnid embryos the greatest research needs are to understand how sediment transport affects the intragravel environment and how these changes affect embryo development and survival. Although a sediment intrusion model [*Alonso et al.*, 1996] has been developed to predict the within-redd sediment accumulation and dissolved oxygen status by considering all the environmental factors that affect embryo survival, the model was not developed specifically to evaluate the probability of embryo survival. This study is intended to develop a framework for assessment of embryo survival in gravel beds subject to fine-sediment deposition. Such a model should take into account the joint effects of multiple factors on embryo survival. The predicted embryo survival can then be further incorporated into management schemes for enhancement of incubation habitat. The relative sensitivity of embryo survival to three environmental factors is investigated. The proposed model is then applied to determine the preferred timing of flushing flows required to remove fine sediment deposits.

2. Factors Influencing Survival of Salmonid Embryos

Prior to modeling embryo survival, it is essential to clarify the factors that influence the survival of salmonid embryos. The probability of survival for salmonid embryos depends on a complex of interacting factors shown in Figure 2, one of the most important of which is oxygen supply rate, which in turn, depends on dissolved oxygen concentration and apparent velocity [*Food and Agriculture Organization* (*FAO*), 1998]. The other two major factors include rate of oxygen uptake (i.e., oxygen demand) and location of embryos in spawning gravels. Figure 2 reveals the fact that apparent velocity is directly influenced by sediment deposition through its effects on reduction of substrate permeability; however, it appears that apparent velocity is irrelevant to factors 1, 6, 7, and 8 (see Figure 2). Because this study is focused on the impacts of sediment deposition on embryo survival, only the governing factors related to apparent velocity (within the dashed box in Figure 2) are concerned herein. If factors 1, 6, 7, and 8 remain unchanged, the probability of embryo survival should only respond to the variation of apparent velocity. Consequently, to establish a relationship between embryo survival and fines content, the reduction of substrate permeability by sediment deposition must first be evaluated. The reduced substrate permeability is linked to an intragravel flow model for estimation of apparent velocity. Then, survival rate is predicted with an empirical relationship connecting apparent velocity with embryo survival. The details of the model components are described in the subsequent sections.

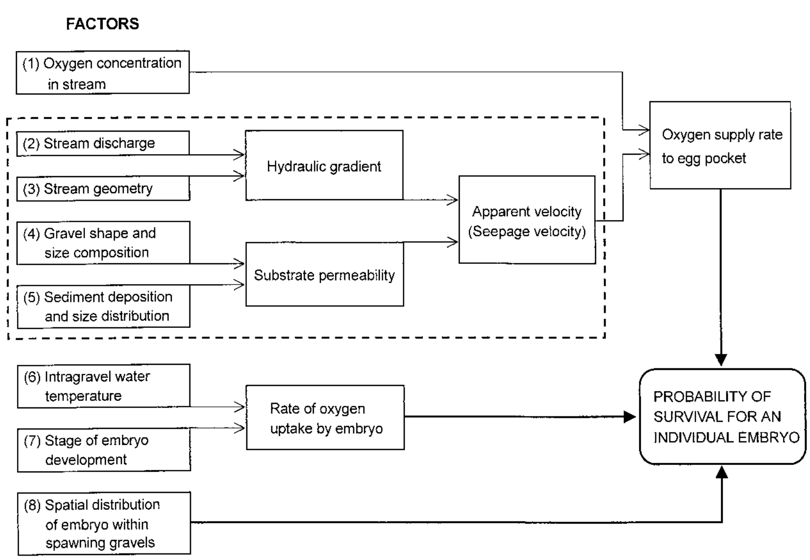

Figure 2. Factors influencing survival of salmonid embryos. Governing factors related to apparent velocity are within the dashed box.

3. Modeling of Embryo Survival

3.1. Relationship Between Sediment Deposit and Substrate Permeability

Fine sediments accumulated in the voids of a porous medium can exert hydraulic resistance on the flow through the medium. *Sakthivadivel* [1966] has compared several hydraulic models describing such a resistance. From a series of laboratory experiments he concluded that the one based on hydraulic radius theory gave the most satisfactory results. The hydraulic radius model is represented by a nonlinear relationship between the reduced permeability and fines content:

$$\frac{K}{K_0} = C_1 \frac{n_e^3}{(1-n_e)^2} + C_2\left(\frac{d_m}{D_f}\right) e^3\sigma, \qquad (1)$$

where K_0 is the permeability of the clean framework; K is the reduced permeability of framework resulting from deposition of matrix material; σ is the specific deposit, defined as (solid volume of sediment deposits)/(bulk volume of framework inclusive of void space); n_e is effective porosity of framework, equal to $[n_0 - (e+1)\sigma]$, in which n_0 is the porosity of the clean framework and e is the void ratio of matrix material; D_f and d_m are the representative diameters of the framework and matrix materials, for which D_{15} and d_{85} were suggested by *Sherard et al*. [1984]; and C_1 and C_2 are the coefficients to be determined. Conceptually, the intragravel flow can be divided into two portions, namely, the flow through the pore spaces that are not occupied by matrix materials and the flow through the interstices of fine sediments. Given typical values of porosity for alluvial sediments range from 0.33 to 0.52 [*Davis and DeWiest*, 1966; *Jobson and Carey*, 1989], herein I have employed the average values of porosity from three salmonid spawning creeks in the north coastal California [*Lisle*, 1989]. The magnitudes of porosity for framework and matrix materials are 0.42 and 0.35, respectively. Employing the concept that the permeability of a porous medium is proportional to the square of the grain diameter [*Bear*, 1972], I evaluate the coefficients by two extreme conditions, one for the clean framework and the other for the framework saturated with fine-sediment deposits. The modified relationship can be expressed as

$$\frac{K}{K_0} = (4.54)\,\frac{(0.42-1.54\sigma)^3}{(0.58+1.54\sigma)^2} + (3.66)\left(\frac{d_s}{D_g}\right)^2 \sigma, \qquad (2)$$

where D_g and d_s are the characteristic diameters of the framework and matrix materials; for uniform materials they can be the median diameters, whereas for nonuniform particle sizes, D_{15} and d_{15} are recommended. The first and second terms on the right-hand side of (2) are related to the flows through the effective pores and the sediment matrix, respectively. For a clean framework (i.e., $\sigma = 0$), the second term is ineffective. However, the first term vanishes when the pores are saturated with fine sediment (i.e., $\sigma = 0.42(1-0.35) = 0.273$). Given the ratio of sediment to gravel sizes, one can use (2) to evaluate the reduced substrate permeability with the content of fine sediment deposited.

3.2. Relationship Between Substrate Permeability and Apparent Velocity

Sediment-laden streamwater enters the spawning gravels in the high-pressure region (upstream face of tailspill) and leaves the substrate in the low-pressure region (downstream face of tailspill) [*Thibodeaux and Boyle*, 1987; *Jobson and Carey*, 1989]. The typical path of this current is shown in Figure 1. Previous studies have identified two distinct modes of fine-sediment intrusion and deposition into salmonid gravels [*Alonso et al*., 1996]. For suspended sediment (such as silt) some enters the bed and deposits down to the bottom of the gravel substrate [*Einstein*, 1968]. However, for fine bed load sediment (such as sand) the gravels tend to filter out the fines carried by the water, thus forming a sand seal in the surface layer of the gravel bed that inhibits further infiltration of sediment [*Beschta and Jackson*, 1979]. *Lisle* [1989] pointed out that the main component of sediment infiltrating the bed is fine bed load rather than suspended sediment because of its frequent contact with the bed and ability to fit into framework interstices. Therefore the present study is focused on the Beschta-Jackson intrusion mode; that is, the sediment deposition is taking place in a surface layer. The permeability of the sand seal is relatively low compared to the surrounding gravels. A two-layer model based on Darcy's law can be used to quantify the flow through spawning gravels [*Milhous*, 1982]. The apparent velocity through the two-layer redd gravels with surface flow across the bedding plane can be determined by

$$V' = (h/L_1)\,K_2/[(L_2/L_1) + (K_2/K_1)], \qquad (3)$$

in which L_1 is the length of flow path through layer 1 (sand seal), L_2 is the length of flow path through layer 2 (surrounding gravels), K_1 and K_2 are the permeability of layer 1 and 2, respectively, h is the total pressure head drop between the upstream and downstream faces of the tailspill, which sums the differences of hydrodynamic and hydrostatic pressure heads. The ratio of K_1/K_2 used in (3) is simply the K/K_0 value calculated from (2) because σ represents the specific deposit in layer 1. For any finite L_1, L_2, h, and K_2 (or K_0), (3) indicates that the limit on the velocities is zero when K_1 (or K) becomes infinitely small. Such a limiting case would occur only when a dense seal is formed in layer 1.

3.3. Relationship Between Apparent Velocity and Embryo Survival

As described in section 2, for this study the apparent velocity will serve as an indicator variable to quantify embryo survival. The experimental data of *Cooper* [1965] were used to develop an empirical relationship between apparent velocity and survival rate. Cooper's data, which were mainly based on the results of sockeye salmon (*Oncorhynchus nerka*) embryos, showed that an 89% embryo survival rate could be achieved at an apparent velocity of 0.034 cm/s, whereas only 2% survived at 0.00039 cm/s. The regression relationship is given below, with $R^2 = 0.993$ (sample size $n = 8$):

$$S = -17.6(\log V')^2 - 39.6(\log V') + 68.7, \qquad (4)$$

in which S is percent survival and V' is apparent velocity (in cm/s). Since the maximum survival in Cooper's data is 89%, the validity of (4) for $S \geq 90$ is not proven. A concern with regard to (4) is that deviations in such a relationship may exist among different species. However, according to a study by *Shirazi and Seim* [1979], both field and laboratory data demonstrated a very strong and unique correlation between embryo survival and geometric mean diameter of the bed material, irrespective of the species involved. Although apparent velocity is a function of the hydraulic gradient as well as substrate grain size (Figure 2), it is believed that (4) represents a general trend of the $S - V'$ relationships to an acceptable extent.

Table 1. Base Values and Ranges of Model Parameters

Parameter	Base Value	Range	Sources of Data (Applicable Species)
D_g/d_s	14	7–30	*Lisle* [1989]
L_1	8 cm	5–10 cm	*Beschta and Jackson* [1979]
		6.4 cm	*Lisle* [1989]
L_2	280 cm	maximum redd length: 280–350 cm	*Kondolf and Wolman* [1993]
			FAO [1998] (Chinook salmon)
		minimum redd size: 100–150 cm	*Burner* [1951] (Chinook salmon)
		redd tail length: 200–400 cm	*Crisp and Carling* [1989] (80–90 cm long salmonids)
h	4 cm	1–10 cm (mostly ≤4 cm)	*Kondolf et al*. [1993]
K_2 (or K_0)	3 cm/s	1–5 cm/s (median: 3 cm/s)	*Chapman et al*. [1986] (Chinook salmon)
d_s/D_g	0.07	0.03, 0.05, 0.07, 0.09, 0.11	
h/L_1	0.5	0.2, 0.3, 0.5, 0.8, 1.5	
L_2/L_1	35	15, 25, 35, 45, 55	

The target species is Chinook salmon.

3.4. Determination of Model Parameters

To implement the embryo survival model described in the preceding sections, one needs some reference values that can be used as the base of model parameters. In this study, Chinook salmon is selected as the target species because of the availability of data; thus the parameter values corresponding to this species are used as the base of the model. Determinations of the base values and the variation ranges of the model parameters are described in the following, and a summary of the parameter values is given in Table 1.

1. The data summarized by *Lisle* [1989] indicate that for nonuniform sediments the surface seal is formed when the ratio of gravel to sediment sizes, D_g/d_s, lies in the range between 7 and 30. If the ratio is >30, the difference between the framework and matrix grain sizes is large enough to allow infiltration of fines into the subsurface layers, whereas no entry of fines to the framework occurs if the size ratio is <7. In other words, the surface seal forms when the sediment-gravel size ratio, d_s/D_g, is between 0.033 and 0.14. Accordingly, the d_s/D_g values of 0.03, 0.05, 0.07, 0.09, and 0.11 are used for sensitivity analysis, of which 0.07 is selected as the base value. Although the reported ratios are based on the median diameters, I adopt these values for the analysis since the data on D_{15} and d_{15} are not available. The parameter d_s/D_g stands for the characteristics of matrix and framework materials and is thus independent of fish species.

2. *Beschta and Jackson* [1979] noted that the fine sands added to the flow over clean gravels (for which $D_g/d_s = 30$) established a sand seal in the upper 5–10 cm of the bed. *Lisle* [1989], using the average properties of the sands and gravels (for which $D_g/d_s = 6$–8.5) from three creeks in the north coastal California, further estimated the maximum seal thickness as 6.4 cm. The seal thickness is generally scaled by the particle sizes of the sand and surface gravel. However, as described above, the surface seal is formed only when $7 < D_g/d_s < 30$, and since the average matrix/framework porosity from *Lisle* [1989] was used for deriving (2), a median of the reported values (i.e., 8 cm) is adopted herein as the base of L_1.

3. The data compiled by *Kondolf et al*. [1993] were used for surveying the possible range of h. The data include 40 sets of water surface slopes, average flow depths, and velocities across spawning redds. It is estimated from these data that for Chinook salmon the maximum h value is of the order of 10 cm. The data also reveal that the hydraulic pressure heads most frequently encountered in natural spawning streams are no greater than 4 cm; hence I take 4 cm as the base value of h. With $L_1 = 8$ cm the h/L_1 values of 0.2, 0.3, 0.5, 0.8, and 1.5 are used to cover the entire range of variation, of which 0.5 is a base value.

4. The length of intragravel flow path L_2 is correlated to the dimension of the spawning redd. In general, redd dimensions vary with fish length, gravel size, and flow conditions [*Crisp and Carling*, 1989]. It is reported that the maximum redd length is ~3.5 times fish length [*FAO*, 1998]. The data presented by *Kondolf and Wolman* [1993] show that the female fish length for Chinook salmon is between 80 and 100 cm, which results in an estimation of the maximum redd length, i.e., 280–350 cm. According to the field studies conducted by *Crisp and Carling* [1989], the tail length of the redd constructed by the female of similar size (fish length of 80–90 cm) ranges from 200 to 400 cm. *Burner* [1951] has made observations on the spawning nests of Columbia River Chinook salmon. His graphical illustrations reveal that the minimum redd length is ~100–150 cm. Recognizing that L_2 is somewhat less than the total redd length, herein I select 280 cm as the base of L_2 (which is the lower value of maximum redd length and also close to the median redd tail length). To cover the possible range of L_2, I use 15, 25, 35, 45, and 55 as the L_2/L_1 values for sensitivity analysis.

5. Investigations on the 15 redds prepared by Chinook salmon in the Columbia River indicated that the permeability of egg pockets is in the range between 1 and 5 cm/s, with a median of 3 cm/s [*Chapman et al*., 1986]. Accordingly, 3 cm/s is used herein as the base value of the framework permeability (K_2 or K_0).

4. Results and Discussion

4.1. Substrate Permeability Versus Sediment Deposition

Variations of substrate permeability with sediment deposition are shown in Figure 3, where various curves are for the size ratios of 0.03–0.11, respectively. Figure 3a reveals that the variation trends of the curves are essentially very similar, with K/K_0 ranging from 1 (at $\sigma = 0$) to the magnitudes <0.02 (at $\sigma > 0.2$). The differences between these curves become apparent with an increased value of the specific deposit. The lower portion of these curves is illustrated in Figure 3b, where one can see that the K/K_0 value is positively correlated to the size ratio. In other words, the reduction of substrate permeability induced by deposition of the smaller-size sediment is more substantial for a given specific deposit. When $\sigma = 0.25$ (interstices almost saturated with fine sediment), for example, the

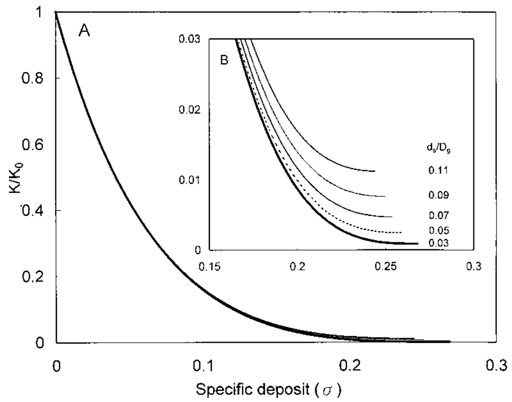

Figure 3. Variations of substrate permeability with sediment deposition for various sediment-gravel size ratios: (a) the entire range of specific deposit ($0 < \sigma < 0.273$) and (b) enlargement of the lower portion ($0.15 < \sigma$).

reduction of permeability increases 1% (i.e., K/K_0 from 1.1 to 0.1%) if the size ratio decreases from 0.11 to 0.03. It is believed that the greater reduction of substrate permeability caused by finer sediments is attributed to the lower permeability (or smaller pore sizes) associated with them.

4.2. Apparent Velocity Versus Sediment Deposition

Figures 4a, 5a, and 6a demonstrate the relationships between apparent velocity and specific deposit for various d_s/D_g, h/L_1, and L_2/L_1, respectively. They are all consistent in that apparent velocity decreases as sediment deposit increases, although in different fashions. It appears that the variation trends for the lower portion of the $V' - \sigma$ curves in Figures 4a are similar to those of the $K/K_0 - \sigma$ curves in Figure 3b. Both show that the differences between the curves increase as a function of the σ value. This common trend becomes reason-

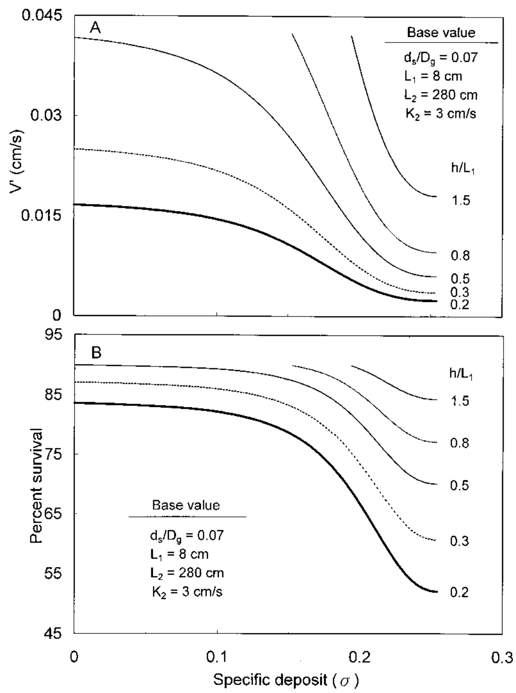

Figure 5. Variations of (a) apparent velocity and (b) embryo survival with sediment deposition for various hydraulic pressure heads.

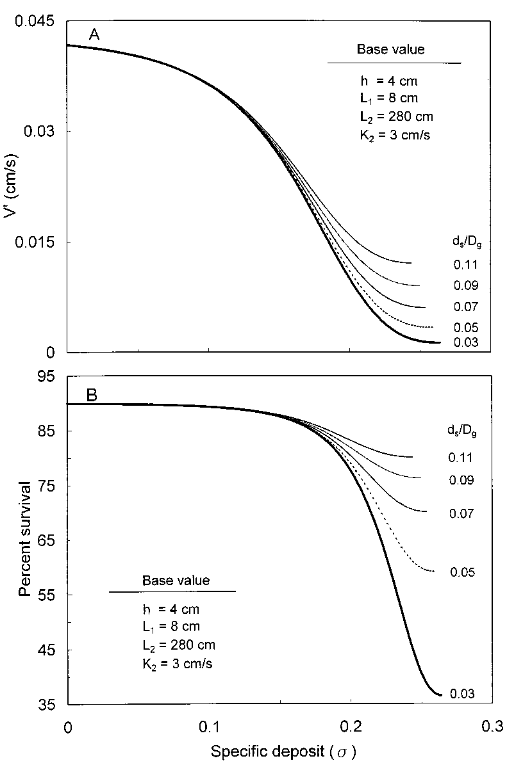

Figure 4. Variations of (a) apparent velocity and (b) embryo survival with sediment deposition for various sediment-gravel size ratios.

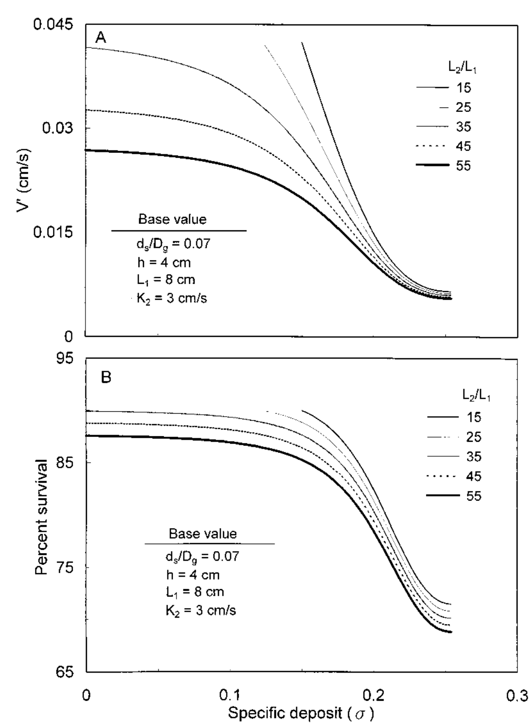

Figure 6. Variations of (a) apparent velocity and (b) embryo survival with sediment deposition for various lengths of intragravel flow path.

able if one recognizes that the differences between the apparent velocities calculated with (3) directly result from the differences of K_1/K_2 terms determined by (2), when the base parameters are used. Meanwhile, Figure 4a reveals that apparent velocity is greater for coarser sediment at a given specific deposit. For instance, at $\sigma = 0.25$ the apparent velocity increases from 0.0015 to 0.012 cm/s when the size ratio is increased from 0.03 to 0.11. Such a trend is also attributed to the smaller reduction of permeability caused by deposition of coarser sediments.

Figures 5a and 6a demonstrate the $V' - \sigma$ relationships for various pressure heads and path lengths, with a constant size ratio of 0.07. For a given specific deposit, apparent velocity increases with increasing pressure head yet decreases with increasing path length. For example, at $\sigma = 0.25$ the apparent velocity increases from 0.0024 to 0.0182 cm/s as the dimensionless pressure head h/L_1 is increased from 0.2 to 1.5, while the apparent velocity reduces from 0.0066 to 0.0056 cm/s if the dimensionless flow path L_2/L_1 increases from 15 to 55. Figure 6a reveals a clear trend in that the differences between the curves are decreasing with increase of specific deposit. However, the decreasing trends for the differences between the curves in Figure 5a are rather diverse. Although the differences between the curves in Figure 5a are also monotonously decreasing with increase of specific deposit, the variation is not as sharp as that in Figure 6a.

4.3. Embryo Survival Versus Sediment Deposition

Variations of embryo survival with sediment deposition are shown in Figures 4b, 5b, and 6b for various d_s/D_g, h/L_1, and L_2/L_1, respectively. Similar to the variations of $V' - \sigma$ curves, the $S - \sigma$ curves also demonstrate a decreasing trend with increase of sediment deposition. For a given content of fines deposition, survival rate is higher for coarser sediment (Figure 4b), greater pressure head (Figure 5b), or shorter flow path (Figure 6b). For illustration, the $S - \sigma$ curves are examined at $\sigma = 0.25$ (a nearly saturated condition). The embryo survival increases from 41 to 80% as d_s/D_g varies from 0.03 to 0.11 and from 52 to 84% as h/L_1 increases from 0.2 to 1.5, whereas the survival rate reduces from 72 to 69% as L_2/L_1 increases from 15 to 55. Such outcomes result from the greater apparent velocities associated with the coarser sediments, higher pressure heads, or shorter flow paths and thus are consistent with the trends shown in Figures 4a, 5a, and 6a.

Figure 4b shows that the survival rates of various size ratios are nearly identical for $\sigma < 0.15$, whereas the greatest difference can exceed 43% as $\sigma > 0.25$. This indicates that the effect of sediment size on embryo survival becomes dominant when the quantity of fines deposition exceeds a certain value (~50% of the saturation content). However, Figure 4b also indicates that the variation of embryo survival with specific deposit is much steeper for finer sediment. Figure 5b shows that incubating embryos can tolerate higher levels of specific deposit when greater pressure heads are available. For instance, to achieve 85% embryo survival, the maximum tolerable specific deposit would be 0.13 for the lowest pressure head ($h/L_1 = 0.3$), while the tolerable level of σ can be raised to 0.24 as a higher pressure head ($h/L_1 = 1.5$) is imposed. Figure 5b also reveals that the variation of embryo survival with specific deposit is steeper for the lower pressure head. Meanwhile, Figure 6b indicates that the tolerable level of σ for achieving a given survival rate is higher for a shorter flow path. To summarize, the $S - \sigma$ relationships for various parametric conditions are correlated to the corresponding $V' - \sigma$ relationships owing to the fact that transformation of apparent velocity into survival rate depends on a nonlinear relationship given by (4). The model results are consistent with previous simulation results that related embryo survival to mean bed load flux [*Lisle and Lewis*, 1992] because in their model fine-sediment infiltration is a function of the mean bed load flux.

4.4. Sensitivity of Embryo Survival

The $S - \sigma$ relationships in Figures 4b, 5b, and 6b allow one to further discuss the sensitivity of embryo survival to the model parameters. First of all, one may find in Figure 4b the apparent influence of sediment-gravel size ratio on embryo survival. For the smallest size ratio (i.e., 0.03) the survival rate could reduce to 37% as sediment intrusion approaches saturation (i.e., $\sigma > 0.25$), while in Figures 5b and 6b the lowest survival rates still remain at the levels of 52 and 69% for the lowest pressure head and longest flow path, respectively. The maximum survival rate reductions caused by the increase of fines content (i.e., σ from 0 to 0.25) are 53, 32, and 19% for $d_s/D_g = 0.03$, $h/L_1 = 0.2$, and $L_2/L_1 = 55$ in Figures 4b, 5b, and 6b, respectively. These results appear to indicate that embryo survival is most sensitive to the composition of fine sediment or, specifically, the ratio of sediment to gravel sizes. The model results are consistent with previous observations, such as *Peterson and Metcalfe* [1981] and *Tappel and Bjornn* [1983]. The maximum influence of pressure head on embryo survival is ~60% of the maximum influence caused by varying the size ratio. The sensitivity of embryo survival to the intragravel flow path is the least important among the three, ~35% of the value influenced by size ratio.

Furthermore, a common trend demonstrated in Figures 4b, 5b, and 6b is that embryo survival decreases rapidly as the specific deposit exceeds 0.15 (approximately one half of saturation). This implies that incubating embryos are subtly affected by the additional deposition of sediments, particularly at high levels of specific deposit. As the saturation state is reached, the survival reduction caused by the finest sediment (size ratio is 0.03) exceeds 5 times the magnitude caused by the coarsest one (size ratio is 0.11). Likewise, the survival reduction for the lowest pressure head ($h/L_1 = 0.2$) is also >5 times the magnitude for the highest head ($h/L_1 = 1.5$). The model results indicate that various geometric and/or hydraulic conditions would lead to diverse values of embryo survival for given gravel permeability, which coincide with the results obtained by *Chapman* [1988]. For an extreme case, if the spawning redd is loaded with a large quantity of very fine sediments (accompanied by a negligible hydraulic gradient) the anticipated mortality of salmonid embryos would be exceedingly high. On the other hand, regardless of the significant influences of size ratio and pressure head, the difference between the survival rates for the longest and shortest flow paths (i.e., for $L_2/L_1 = 55$ and 15, respectively) is <3% at $\sigma > 0.25$; even the maximum difference is <5% at $\sigma < 0.15$. Apparently, the length of flow path (or the L_2/L_1 value) is not as influential as size ratio or pressure head. Although the foregoing sensitivity analyses were performed separately on each parameter, the model can be potentially used to investigate the combined effect of model parameters on embryo survival.

The results of sensitivity analyses imply that effective increases of embryo survival are possible by means of (1) enlarging the sizes of near-bed sediments that are potentially deposited, (2) increasing the pressure head that drives the intragravel current, or (3) restricting the deposition of sediment into spawning gravels. Generally, the grain size of bed load sediment depends on the streambed shear stress, characteristics of bed material, and availability of the material in the watershed [*Garde and Ranga Raju*, 1985]. The pressure head drop across the tailspill is governed by hydraulic conditions (e.g., flow depth and velocity) and local streambed geometry (e.g., form and grain roughness) [*Thibodeaux and Boyle*, 1987]. Both the sizes of bed load sediments and the pressure head drops vary with natural conditions in streams and thus are difficult to modify. Removal of fine sediment by flushing flows is more likely to be adopted as an alternative to enhance the quality of incubation habitat. An application of the embryo survival model to prescribe the timing of flushing flow release is presented in section 5.

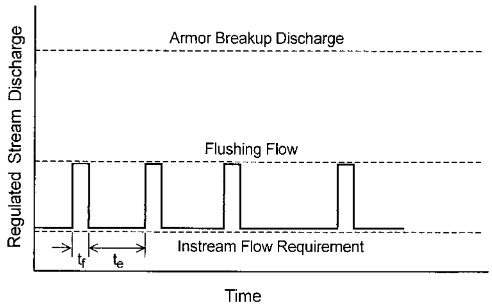

Figure 7. Schematic of the discharge required for maintaining suitable incubation habitat. (Here t_f is the duration of flushing flow; t_e is the interval between flushing flows, or the period of sediment deposition.)

5. Application to Flushing Flow Prescriptions

Flushing flow is the programmed release of a predetermined discharge for a given duration to remove fine sediments from river gravels [*Reiser et al.*, 1989]. In general, prescriptions of flushing flows require establishing the discharge, duration (or total volume), and timing of such flows. Fine sediments can be winnowed from the gravels when the armor layer is entrained, thereby releasing fines from the near subsurface according to the model proposed by *Parker and Klingeman* [1982]. In streams with sufficient gravel supply, one way of flushing the fines from the gravel would be to break up the armor layer. However, if the supply of gravel is limited, the use of the armor breakup discharge as the flushing flow may result in stream armoring with materials too large for spawning or scour of incubating embryos. A number of methods have been suggested for the evaluation of flushing flow requirements. *Reiser et al.* [1989] pointed out that the most reliable method for establishing the discharge of flushing flow is to observe the study stream at various flow levels. It is equally important to determine the best time for implementing flushing flows. From a fisheries perspective the best timing for flushing flows is that which provides the greatest benefits or imparts the least harm to the biotic communities. As stated previously, the action of redd construction removes considerable fines from the spawning gravels. However, for many regions and species, incubation coincides with seasonal run off that results in sediment deposition. Hence maintaining a reasonably clean redd during incubation is important for enhancement of embryo survival. For multipurpose water resources planning, one of the alternative options allows some fine accumulation and periodically increases the flow rate by an appropriate amount to flush fine sediments from the gravels. The proposed embryo survival model can be used to determine how often flushing flows should occur for maintaining a prescribed survival rate.

As a study case, consider the management options for improving the incubation habitat of coho salmon (*Oncorhynchus kisutch*) in Oak Creek, Oregon [*Milhous*, 1982]. The first storm peak in the fall is important in removing the fines from the surface gravels of the incubation habitat. The management issues arise when it is proposed to divert a significant amount of water from the first storm and maintain a minimum instream flow. As a consequence of the peak reduction, removal of fine sediments is significantly restricted. Thus periodic flow increases, as illustrated in Figure 7, are required to flush fine sediments. It has been shown that a discharge of 1.3 m^3/s (45 ft^3/s) is near the critical flow rate associated with armor breakup [*Milhous*, 1982]. Data from Oak Creek suggest that a flushing flow of one half the armor breakup flow would remove most of the fines and not cause significant scour of embryos. The duration of the flow increase, designated as t_f in Figure 7, is equal to the travel time through the stream reach requiring a flushing flow. The interval between flushing flows or the period of sediment deposition, t_e, can be conceptually described by the following expression:

$$\alpha V_R = \int_0^{t_e} R(t)\, dt, \tag{5}$$

where V_R is the volume of the interstitial space within the surface layer (~5–10 cm deep) of the redd gravels, α is the fraction of V_R that can be filled without injury to a prescribed percentage of incubating embryos, and $R(t)$ is the rate at which fines are deposited into the gravel interstices. The rate of deposition is a complex function of many factors such as the near-bed sediment concentration, grain sizes of sediments and gravels, and hydraulic gradient of seepage flow [*Diplas and Parker*, 1985] or fine bed load flux [*Lisle and Lewis*, 1992]. To maintain a prescribed survival rate, $\alpha V_R/V_B$ should not exceed the tolerable level of specific deposit σ_t, where V_B is the bulk volume of the surface layer redd gravels; σ_t can be determined with the proposed $S - \sigma$ relationships (as those illustrated in Figures 4b, 5b, and 6b). Given the σ_t value, one can use Figure 3 (or (2)) to evaluate K_t, i.e., the tolerable minimum permeability corresponding to the prescribed survival rate.

The framework permeability K is reduced with time t during the process of sediment deposition and accumulation, which can be described by the following equation developed for gravel beds [*Schälchli*, 1995]:

$$K(t) = \frac{gL}{v\sqrt{\beta^2 + 2\,\frac{g}{v}\,rhCt}}, \tag{6}$$

in which L is the length of intragravel flow path, equal to $L_1 + L_2$; $\beta = gL/K_0 v$; g is the gravitational acceleration; v is the kinematic viscosity of water; r is the specific infiltration resistance; and C is the near-bed sediment concentration (by weight). The magnitudes of r lie in the range between 2×10^{10} and 2×10^{12} m/kg for natural gravel bed streams [*Schälchli*, 1995]. The near-bed sediment concentrations in most gravel bed rivers are within the range of 10^{-3}–10^{1} kg/m^3 [*Alonso and Mendoza*, 1992; *Schälchli*, 1995]. Replacing $K(t)$ with the tol-

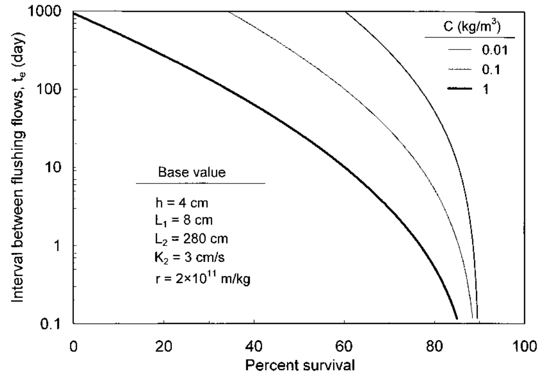

Figure 8. Relationships between timing of flushing flows t_e and prescribed survival rate for various near-bed sediment concentrations.

erable permeability K_t allows one to solve (6) for the period of deposition t_e. Variations of t_e with the corresponding embryo survival are shown in Figure 8, where the three curves demonstrate the $t_e - S$ relationships for average sediment concentrations of 0.01, 0.1, and 1 kg/m^3, respectively. The results reveal that t_e decreases with increase of prescribed survival rate or average sediment concentration, which implies that shorter t_e should be appropriate when higher levels of embryo survival are prescribed or higher near-bed sediment concentrations are imposed. For instance, when a 70% survival rate is to be maintained, the corresponding values of t_e are 300, 30, and 3 days for the sediment concentrations of 0.01, 0.1, and 1 kg/m^3, respectively. However, if the prescribed survival rate is raised to a level of 80%, the corresponding t_e should be reduced to 52, 5, and 0.5 days. For sediment concentration as high as 1 kg/m^3, release of a flushing flow every day (i.e., t_e = 1 day) could maintain a 77% survival rate; however, only a 60% survival could be achieved when t_e is extended to a period of 10 days. It is recommended that the flow diversion projects be adjusted to modify deposition of fine sediments in case the required frequency of flushing flows is too high.

6. Summary and Conclusions

In this study I have linked three quantitative relationships to develop a framework for assessing embryo survival in salmonid spawning gravels subject to fine-sediment deposition. The integrated model is used to evaluate the variations of embryo survival with the quantity of sediment deposited. The base values of the model parameters and their ranges are based on a survey of existing literature. The sensitivity of embryo survival to three environmental parameters is investigated. Deposition of fine sediments into gravel beds reduces substrate permeability, which in turn, decreases intragravel flow velocity and embryo survival. The focus of this study is on the impacts of sediment deposition; thus only the governing factors related to apparent velocity are considered in this paper. The issues related to water quality (such as temperature, dissolved oxygen, and pH value), species differences, temporal and spatial concerns (such as stage of embryo development, variation of sediment deposition during flow events, scour and fill, and distribution of embryos) should be addressed in future studies.

The model results indicate that substrate permeability is sensitive to the intrusion of finer sediment, though the variation trends are very similar for various matrix sizes. For a given specific deposit, apparent velocity increases with the pressure head available yet decreases with the length of flow path. As a result, the corresponding survival rate is higher for coarser sediments, larger pressure heads, or shorter flow paths. Such outcomes are attributed to the greater apparent velocity associated with these conditions. Among the three factors considered, embryo survival is most sensitive to the ratio of fine sediment to gravel sizes. The maximum influence of pressure head on embryo survival is ~60% of the maximum influence of size ratio. The sensitivity of embryo survival to the length of intragravel flow path is the least among the three, ~35% of the value influenced by size ratio. Although the model results presented herein are not verified with field or laboratory tests, the results are consistent with observations of the impacts of sediment deposition on embryo survival, particularly the joint effect of multiple factors.

The embryo survival model is then incorporated with the management options for enhancement of salmonid incubation habitat by flushing flows. As an application example, the assessment framework is used to determine the timing of flushing flows for maintaining a prescribed level of embryo survival. The results imply that the interval between flushing flows t_e should be reduced when higher levels of embryo survival are specified or higher near-bed sediment concentrations are imposed. From a management perspective the proposed framework may well serve as an effective tool for prescribing flushing flow requirements.

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