Uncertainty and Risk Analyses of Egg Survival in Salmonid Spawning Gravels

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ABSTRACT: Natural gravel-bed rivers provide spawning and incubation habitat for salmonids. The intragravel flow benefits the exchange of dissolved oxygen and metabolic waste to maintain an appropriate spawning environment. Deposition of fine sediment into the spawning gravels reduces the interstitial flow and thus the survival rate. An assessment framework has been developed for evaluating egg survival as a function of sediment deposition. The model allows evaluation of the impacts of sediment deposition on embryo survival. The variabilities of egg survival with three selected environmental factors are investigated to evaluate the sensitive content of sediment deposits. A probabilistic point-estimation method is then used to analyze the uncertainty of egg survival. Based on the result, the strategic risk for defining ecological goals is assessed. A fuzzy triangular distribution is used to represent the potentially specified ecological goal. Given the uncertainties, the result indicates that the strategic risk increases with the mode and the lower limit of the specified egg survival rate.

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, where the female excavates a pit and releases fertilized eggs into the bottom. After spawning, the female resumes digging upstream to bury the area of egg deposition. The embryos are therein protected against bedload motion and scour during high flows. The typical morphology of the resultant nest (or redd), 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. This type of flow benefits the exchange of dissolved oxygen and removal of metabolic waste to maintain an intragravel environment crucial for embryo survival (Cooper, 1965).

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. 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. The first author (Wu, 2000) proposed an assessment framework for modeling egg survival affected by sediment deposition into spawning gravels. The model allows evaluation of the impacts of sediment deposition on embryo survival. However, the input data and parameters of the model are subject to uncertainty. A probabilistic point-estimation method is used herein to analyze the uncertainty of egg survival. Based on the result, an assessment of strategic risk for defining ecological goals is performed. A fuzzy triangular distribution is used to represent the potentially specified ecological goal. Given the uncertainties, the resultant risk surface indicates that the strategic risk increases with the mode and the lower limit of the specified egg survival rate.

2 EGG SURVIVAL MODEL

The egg survival model integrates three quantitative relationships to evaluate the variations of (1) substrate permeability with sediment deposition; (2) apparent velocity with substrate permeability; and (3) egg survival rate with apparent velocity. The model components are described in the following sections.

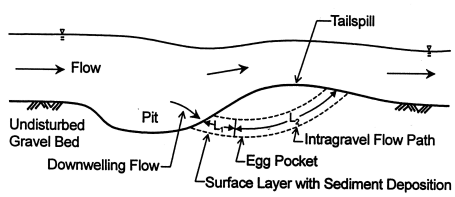

Figure 1: Typical morphology of spawning redd and sketch of intragravel flow.

2.1 Variation of substrate permeability with sediment deposition

Fine sediments accumulated in the voids of a porous medium can exert hydraulic resistance on the flow through the medium. Based on the hydraulic radius model (Sakthivadivel, 1966), a relationship describing the variation of substrate permeability with the content of sediment deposition is formulated (Wu, 2000):

$$\frac{K}{K_0} = (4.54)\frac{(0.42-1.54\sigma)^3}{(0.58+1.54\sigma)^2} + (3.66)\left(\frac{d_s}{D_g}\right)^2 \sigma \quad (1)$$

where K_0 is the permeability of the clean framework; K is the reduced permeability of framework resulting from sediment deposition; the specific deposit σ is defined as (solid volume of sediment deposits/bulk volume of gravel framework); D_g and d_s are the diameters of the framework and matrix materials. For a clean framework (i.e. $\sigma = 0$), the second term is ineffective; however, the first term vanishes when the pores are saturated (i.e. $\sigma = 0.273$).

2.2 Variation of apparent velocity with substrate permeability

Streamwater enters the spawning gravels in the high-pressure region and leaves the substrate in the low-pressure region (Figure 1). The gravels on the streambed tend to filter out the fines carried by the water, with a sand seal formed in the area of sediment intrusion. 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 spawning gravels with surface flow across the bedding plane can be determined by:

$$V' = \frac{(h/L_1)K_2}{(L_2/L_1)+(K_2/K_1)} \quad (2)$$

in which L_1 is the length of path through layer 1 (sand seal); L_2 the length of path through layer 2 (surrounding gravels); K_1 and K_2 the permeability of layer 1 and 2, respectively; h is the total pressure-head drop between the upstream and downstream faces of tailspill. The ratio of K_1/K_2 used in Eq. (2) is simply the K/K_0 value calculated from Eq. (1). For any finite L_1, L_2, h, and K_2 (or K_0), Eq. (2)

indicates that the limit on the velocities is zero when K_1 (or K) becomes infinitely small.

2.3 Variation of egg survival with apparent velocity

The experimental data (Cooper, 1965) were used to develop an empirical relationship between apparent velocity and survival rate. The regression relationship is given below, with $R^2 = 0.993$:

$$S = -17.6(\log V')^2 - 39.6(\log V') + 68.7 \quad (3)$$

in which S is percent survival; V' is apparent velocity in cm/s. Since the maximum survival in Cooper's data is 89%, the validity of Eq. (3) for $S \geq 90$ is not proven.

2.4 Determination of parameter values

Based on a survey of existing literature (Wu, 2000), the values of the model parameters are determined (listed in Table 1).

Table 1. Base values and ranges of model parameters

Variable	Base	Range
L_1	6 cm	5-10 cm
		6.4 cm
L_2	120 cm	Average redd size: 100-150 cm
		Redd length = 3.5 *FL* (*FL* = 24-74 cm)
h	3 cm	1-10 cm (mostly $\leq$ 3 cm)
K_2 (or K_0)	5 cm/s	5 cm/s
		1-5 cm/s
d_s / D_g	0.06	0.02, 0.04, 0.06, 0.08, 0.1
L_2 / L_1	20	10, 15, 20, 25, 30
h / L_1	0.5	0.2, 0.3, 0.5, 1.0, 2.0

3 VARIABILITIES OF EGG SURVIVAL

Variations of egg survival with sediment deposition are shown in Figures 2 (a), (b), and (c) for various d_s / D_g, h / L_1, and L_2 / L_1, respectively.

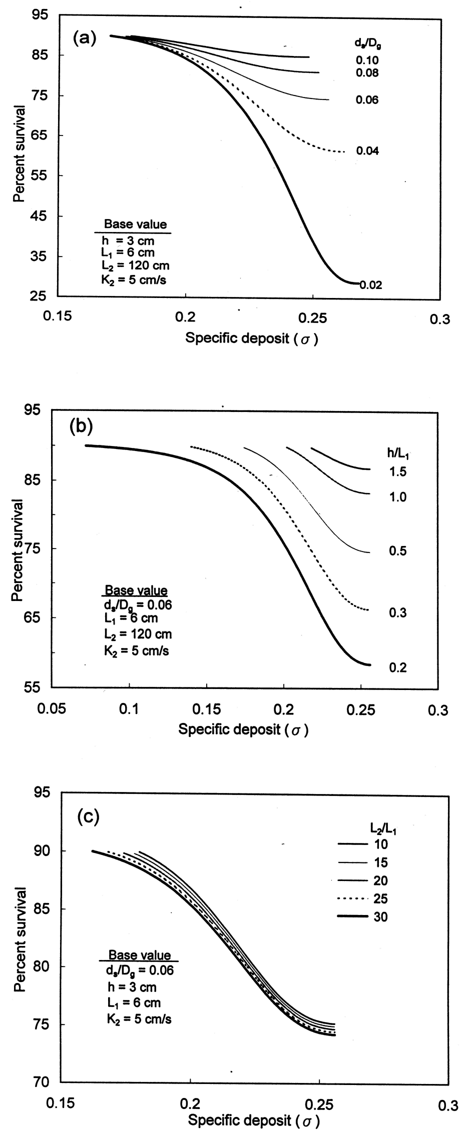

Figure 2: Variabilities of egg survival for various (a) d_s / D_g; (b) h / L_1; and (c) L_2 / L_1.

A common trend demonstrated in these figures is that egg survival reduces sharply as the specific deposit exceeds 0.2. 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 = 0.02) exceeds 10 times the magnitude caused by the coarsest one (size ratio = 0.1). Likewise, the survival reduction for the lowest pressure head (h/L_1 = 0.2) is also greater than 10 times the magnitude for the highest head (h/L_1 = 1.5). On the other hand, the difference between the survival rates for the highest and lowest values of L_2/L_1 (i.e. 30 and 10) is less than 1% at $\sigma > 0.25$; even the maximum difference is less than 2% at $\sigma < 0.2$. The variabilities of egg survival for the three selected environmental factors indicate that the sensitive content of sediment deposits lies approximately in the range between 0.15 and 0.25, with a mean of 0.2. These values are used in the uncertainty analysis.

4 UNCERTAINTY ANALYSIS

A probabilistic point-estimation method (Rosenblueth, 1981) is used herein to analyze the uncertainty of egg survival. For a function $W = g(X)$ involving a single stochastic parameter X, the locations of two points, x_+, x_-, and the corresponding probability mass, p_+, p_-, are determined to preserve the first three moments of the stochastic parameter X. These quantities are computed as the following:

$$
\begin{aligned}
x_+ &= \mu + z_+ s \\
x_- &= \mu - z_- s \\
p_+ &= \frac{z_-}{z_+ + z_-} \\
p_- &= 1 - p_+ \\
z_+ &= \frac{\gamma}{2} + \sqrt{1 + \left(\frac{\gamma}{2}\right)^2} \\
z_- &= z_+ - \gamma
\end{aligned}
\tag{4}
$$

in which μ, s, and γ are the mean, standard deviation, and skew coefficient of the stochastic parameter X . For multivariate problems involving n correlated random variables, $W = g(X_1, X_2, \cdots, X_n)$, the univariate algorithm is applied to define the two point values for each random variable. The mth order moment about the origin of model output, μ'_m, can be computed by

$$\mu'_m = E(W^m) \cong \sum_{\delta_1=+,-} \cdots \sum_{\delta_n=+,-} p_{(\delta_1,\cdots,\delta_n)} \cdot w^m_{(\delta_1,\cdots,\delta_n)} \tag{5}$$

in which subscript, δ_i , $i = 1,\cdots,n$, is a sign indicator and can only be + or - representing the input parameter X_i having the value of x_{i+} or x_{i-} , respectively. $w_{(\delta_1,\cdots,\delta_n)}$ is the value of model output at $(x_{1,\delta_1}, x_{2,\delta_2}, \cdots, x_{n,\delta_n})$, of which the weighting factor (or probability mass), $p_{(\delta_1,\cdots,\delta_n)}$, is determined by

$$p_{(\delta_1,\cdots,\delta_n)} = \prod_{i=1}^{n} p_{i,\delta_i} + \sum_{i=1}^{n-1}\left(\sum_{j=i+1}^{n} \delta_i \delta_j a_{ij}\right) \tag{6}$$

in which p_{i,δ_i} represents the probability mass at point x_{i,δ_i} , and a_{ij} is determined by

$$a_{ij} = \frac{\rho_{ij}/2^n}{\sqrt{\prod_{i=1}^{n}\left[1 + \left(\frac{\gamma}{2}\right)^2\right]}} \tag{7}$$

where ρ_{ij} is the correlation coefficient between random variables X_i and X_j .

Table 2. Statistics of stochastic variables

Variable	**Mean**	**Std. Dev.**
σ	0.2	0.05
d_s/D_g	0.06	0.03
h/L_1	0.5	0.25
L_2/L_1	20	10

The values of mean and standard deviation for model parameters are provided in Table 2, where the means are represented by the base values and the coefficient of variation is 0.5 for the three parameters. The correlation matrix is given in Table 3.

Table 3. Correlation between model input and parameters

Variable	σ	d_s / D_g	h / L_1	L_2 / L_1
σ	1.0	0.25	0.25	-0.25
d_s / D_g		1.0	0.25	0.25
h / L_1			1.0	-0.25
L_2 / L_1				1.0

Given these conditions, the probability point-estimation method results in a mean survival rate of 0.58, standard deviation of 0.26, and a negative skewness of -1.1. Since the values of egg survival rate are bounded (i.e. between 0 and 1), the beta distribution is appropriate for the probability density function (pdf) of egg survival. The best fits to the computed probability mass distribution and cumulative probability distribution indicate that the pdf of egg survival can be represented by a beta distribution given below, with $q = 3$ and $r = 2$:

$$
\begin{aligned}
f_S(\xi) &= \frac{1}{B(q,r)} \xi^{q-1}(1-\xi)^{r-1} \qquad 0 \le \xi \le 1 \\
B(q,r) &= \frac{\Gamma(q)\cdot\Gamma(r)}{\Gamma(q+r)}
\end{aligned} \tag{8}
$$

where Γ is gamma function. The cumulative probability distributions obtained from Rosenblueth's probabilistic point-estimation method and beta distribution are shown in Figure 3.

5 RISK ANALYSIS

The strategic risk for defining ecological goals in the projects involving restoration or improvement of stream eco-environmental status is evaluated herein. From a resource management perspective, the strategic risk is the probability of egg survival rate being less than the specified ecological goal, which can be expressed as

$$
\begin{aligned}
R &= \mathrm{Prob}[S < G] \\
&= \int_0^1 f_G(\zeta)\left[\int_0^G f_S(\xi)d\xi\right]d\zeta
\end{aligned} \tag{9}
$$

where R is the strategic risk; G is the specified ecological goal; f_G is the pdf of the specified ecological goal; f_S is the pdf of the egg survival rate, given by Eq. (8). A rigorous definition of f_G would require a large number of data; however, in reality information is often sparse. A method for treating vague or imprecise information is to employ fuzzy arithmetic (Ross, 1995). A fuzzy number describes the uncertainty with a membership function representing the possibility that the quantity may take on a certain value. The triangular shape is frequently used as a representation of fuzzy number. This concept is adopted herein to define f_G because it is more consistent with the nature of the information typically available. The pdf of the specified ecological goal, f_G, can be expressed as the following (shown in Figure 4):

$$
\begin{aligned}
f_G(\zeta) &= \frac{2}{b-a}\left(\frac{\zeta-a}{m-a}\right) \quad \text{for } a \le \zeta \le m \\
&= \frac{2}{b-a}\left(\frac{b-\zeta}{b-m}\right) \quad \text{for } m \le \zeta \le b
\end{aligned} \tag{10}
$$

where m is the mode, a and b are the lower and upper limits of the distribution, of which $a \le m$ and $b = 0.9$ in this study. With f_S and f_G replaced by Eqs. (8) and (10), direct integration of Eq. (9) yields the distribution of strategic risk as a function of m and a. The resultant risk surface is illustrated in Figure 5, where one can see that R increases with both m and a. In conclusion, given the uncertainties, the strategic risk for defining ecological goals increases with the mode and the lower limit of the specified egg survival rate.

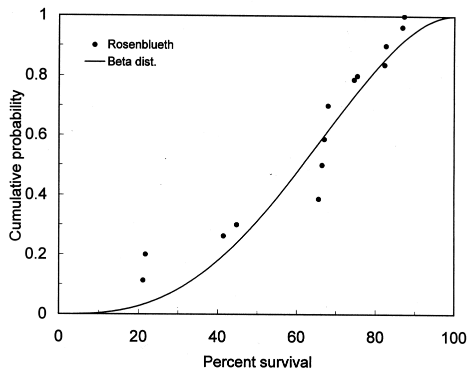

Figure 3: Comparison of cumulative probability distributions obtained from point-estimation method and beta distribution.

6 SUMMARY AND CONCLUSION

This study investigates the uncertainty of egg survival in salmonid spawning gravels and analyzes the strategic risk for defining ecological goals. A quantitative framework is developed to evaluate egg survival as a function of sediment deposition. The uncertainty of egg survival is analyzed with a probabilistic point-estimation method which indicates that the probability of egg survival fits beta distribution. A fuzzy triangular distribution is employed to represent the pdf of the specified ecological goals. Given these uncertainties, the direct integration method results in a risk surface indicating that the strategic risk for defining ecological goals increases with the mode and the lower limit of the specified egg survival rate. The results of this study provide guidelines for decision-makers of the stream ecology-related projects.

REFERENCES

Cooper, A.C., "The Effects of Transported Stream Sediments on the Survival of Sockeye and Pink Salmon Eggs and Alevin", International Pacific Salmon Fisheries Commission, New Westminster, BC, 1965.

Rosenblueth, E., "Two-point Estimates in Probabilities", *Appl. Math. Modelling*, 5, pp.329-335, 1981.

Ross, T.J., *Fuzzy Logic with Engineering Applications*, McGraw-Hill, NY, 1995.

Sakthivadivel, R., "Theory and Mechanism of Filtration of Non-colloidal Fines through a Porous Medium", *Tech. Rep. HEL 15-5*, UC Berkeley, CA, 1966.

Wu, F-C, "Modeling Embryo Survival Affected by Sediment Deposition into Salmonid Spawning Gravels: Application to Flushing Flow Prescriptions", *Water Resources Research*, in press, 2000.

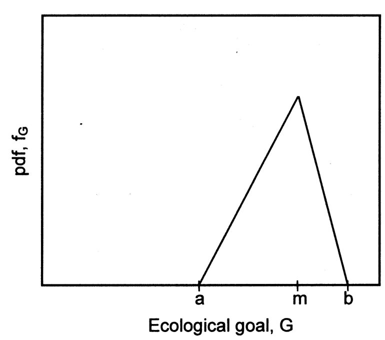

Figure 4: A fuzzy triangular representation of f_G (pdf of specified ecological goal).

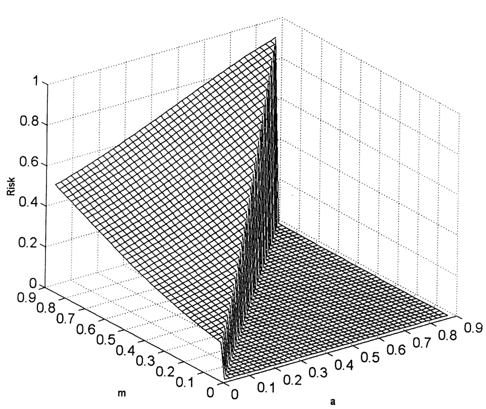

Figure 5: Risk surface showing the strategic risk for defining ecological goals.