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礫石河床鮭魚存活率模式之敏感度分析

Sensitivity Analysis of Embryo Survival Model for Salmonid Spawning Gravels

國立台灣大學生物環境系統工程學系
副教授兼水工試驗所副研究員
吳富春
Fu-Chun Wu

台北市政府環保局
專員
馬昱
Diana Y. Ma

國立台灣大學生物環境系統工程學
研究所碩士生
曾尹玢
Yin-Phan Tsang

摘　要

本文主要針對礫石河床之鮭魚存活率進行敏感度分析。本研究針對礫石河床鮭魚存活率預測模式進行個別參數敏感度分析及組合參數敏感度分析，所探討之三項參數包括：泥砂礫石粒徑比、無因次水頭差及礫石孔隙水流路徑比。個別參數敏感度分析結果顯示泥砂礫石粒徑比爲最敏感參數，且其值之減小對存活率降低之影響甚大，無因次水頭差之影響次之，礫石孔隙水流路徑比之影響則甚微。組合參數敏感度分析結果顯示泥砂礫石粒徑比在搭配無因次水頭差上限值與礫石孔隙水流路徑比下限值時具有最大敏感度，對鮭魚存活率之影響最大。此外，本研究亦利用鮭魚存活率預測模式及沖淤水流模式探討沖淤水流時距之敏感度，針對礫石特性粒徑比、無因次水頭差及礫石孔隙水流路徑比進行個別及組合參數敏感度分析。研究結果顯示礫石特性粒徑比對沖淤水流時距之縮短影響甚鉅，且其在搭配無因次水頭差與礫石孔隙水流路徑比之上限值時有最大之敏感度。本敏感度分析之結果不僅可做爲棲地改善與沖淤水流規劃之依據，更可供後續不確定性分析之參考。

關鍵詞：產卵礫石河床，鮭魚存活率，敏感度分析，沖淤水流，棲地改善。

ABSTRACT

This paper addresses the sensitivity of embryo survival in salmonid spawning gravels. Individual and combined sensitivity analyses are conducted on three parameters of the predictive model for embryo survival, namely, sediment-gravel size ratio d_s/D_g, dimensionless pressure head h/L_1, and ratio of intragravel flow paths L_2/L_1. Individual analysis indicates that reduction of embryo survival rate is most sensitive to d_s/D_g. The results are more sensitive to the decreases in d_s/D_g and h/L_1 than to the increases in the two parameters. The model is least sensitive to L_2 / L_1. The results of combined analysis reveal that d_s / D_g has significant effects on embryo survival, the effects are even greater when h / L_1 is at its upper bound value and L_2 / L_1 is at its lower bound value. In addition, the embryo survival model is incorporated into the flushing flow model to investigate the sensitivity of the interval between flushing flows. It is shown that the characteristic gravel size ratio d_{10} / d_m has significant effects on flushing interval, especially when d_{10} / d_m, h / L_1, and L_2 / L_1 are all at their upper bound values. The results of sensitivity analysis can be used as guidelines for planning of habitat enhancement and flushing flow strategy. The results also provide useful information for further uncertainty analysis.

Keywords: Spawning gravels, Salmonid embryo survival, Sensitivity analysis, Flushing flow, Habitat enhancement.

1. Introduction

Gravel-bed streams are typically characterized by pool-riffle sequences that provide suitable locations for salmonids to use as spawning and incubation habitat. Natural and anthropogenic environmental changes can degrade the quality of incubation habitat. Among the factors that could adversely affect salmonid embryo survival, intrusion and accumulation of fine sediment into the gravel substrate is regarded as one of the most detrimental. A quantitative framework has been developed for predicting embryo survival in spawning gravels as a function of sediment deposition (Wu, 2000). The embryo survival model is further applied to determine the timing of flushing flows. The model parameters were estimated through a survey of existing literature and thus prone to an extent of uncertainty. However, available data are not sufficient for developing accurate probability distributions of the model parameters. For these parameters, an approach that evaluates model sensitivity over the entire range of possible parameter values may be more appropriate. In this paper, we present such a sensitivity approach that is more thorough in the sense that it not only examines the model sensitivity due to individual parameter uncertainty, but also includes the combined effects of errors in multiple parameter values. The sensitivities of embryo survival and flushing interval on parameter values are investigated.

2. Overview of Embryo Survival Model and Flushing Flow Prescriptions

The target model used to demonstrate our analysis is the salmonid embryo survival model developed by Wu (2000). Three governing equations of which clearly state the relationships between sediment deposit and substrate permeability, substrate permeability and apparent velocity, apparent velocity and embryo survival, respectively. It is proposed for the assessment of embryo survival in salmonid spawning gravel beds subject to fine-sediment deposition. With the quantity of sediment deposited, the integrated model can be used effectively to evaluate the variations of embryo survival.

2.1 Salmonid Embryo Survival Model

The framework that links three quantitative relationships for assessing embryo survival in salmonid spawning gravels affected by fine sediment deposition is described below.

2.1.1 Relationship between sediment deposit and substrate permeability

Hydraulic resistance can be exerted on the flow through the accumulation of fine sediments in the voids of a porous medium. The mechanism is represented, with satisfactory results, by the following nonlinear relationship (Wu, 2000):

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

in which K_0 and K represent the permeability of clean gravel bed, and reduced permeability resulting from sediment deposits; σ is the specific deposit, defined as (solid volume of sediment deposits)/(bulk volume of gravel bed including void space); D_g and d_s are the characteristic diameters of the gravel bed and the sediment deposits, for uniform materials they can be the median diameters, whereas for nonuniform particle sizes, D_{15} and d_{15} are recommended (Wu, 2000). For a clean gravel bed (when σ=0), the second term on the right is ineffective. While the first term vanishes when the pores are saturated with fine sediment (i.e., σ=0.42/1.54=0.273).

2.1.2 Relationship between substrate permeability and apparent velocity

Sediment-laden streamwater tends to flow through the spawning gravels from the high-pressure to the low-pressure region. A two-layer model is used to quantify this fine-sediment intrusion mode, and the apparent velocity through the two-layer redd gravels with surface flow across the bedding plane can be determined by

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

in which L_1 and L_2 are the length of flow path through layer 1 (sand seal) and layer 2 (surrounding gravel); K_1 and K_2 are the permeability of layer 1 and 2, respectively; and h is the total pressure head drop between the two regions. The ratio of K_1/K_2 used in (2) is simply the K/K_0 value calculated in (1) because σ represents the specific deposit in layer 1.

2.1.3 Relationship between apparent velocity and embryo survival

Apparent velocity is served as an indicator variable to quantify embryo survival in this model, and an empirical relationship between apparent velocity and survival rate was developed through sets of experimental data (Wu, 2000):

$$S = -17.6(\log V') - 39.6(\log V') + 68.7 \quad \text{............(3)}$$

in which S is percent survival and V' is the apparent velocity (in cm/s).

2.2 Flushing Flow Prescriptions

Flushing flow prescriptions, in general, include the specifications of discharge, duration and timing of such flows to remove fine sediments from river gravels for enhancement of incubation habitat. The proposed embryo survival model can be further applied to determine the interval between flushing flows for maintaining a prescribed survival rate.

The permeability K is reduced with time t during the process of sediment deposition, which can be described by the siltation equation developed for gravel beds (Schälchli, 1995):

$$K(t) = \frac{gL}{\upsilon\sqrt{\beta^2 + 2\frac{g}{\upsilon}rhCt}} \quad \text{...............................(4)}$$

in which L is the length of intragravel flow path, equals to $L_1 + L_2$; $\beta = gL/K_0\upsilon$; g is the gravitational acceleration; υ is the kinematic viscosity of water; C is the near-bed sediment concentration (by weight), and r is the specific infiltration resistance. According to Schälchli (1995), r can be expressed as the following equation:

$$r = \frac{7.43\times10^2}{(d_{10}/d_m)^{3.5}\times[(h/L_1)/(1+L_2/L_1)]^{0.67}} \quad \text{.......(5)}$$

where d_{10} represents the characteristic gravel size such that 10% of the bed material (by weight) are smaller and d_m represents the mean gravel size; h, L_1 and L_2 are defined in the previous section.

For a prescribed survival rate S, the tolerable minimum permeability K_t can be calculated through (2) and (3). Replacing $K(t)$ with K_t allows one to solve (4) for the period of deposition t_e, which is also the interval between flushing flows. Further details are presented in Wu (2000).

3. Sensitivity Analysis

Individual analysis and combined analysis are used in this paper to investigate the effects of parameter errors on the embryo survival model results. Both analyses have been previously applied to study the optimal groundwater remediation policies (Minsker and Shoemaker, 1998). Individual analysis is the traditional approach to sensitivity analysis, which allows us to assess the effects of perturbation in one parameter at a time. However, it does not reveal the effects of simultaneous errors for models with multiple parameters. For each parameter, the model results are examined for the base case (or best estimate) of the parameter value μ, and also for the lower and upper bound parameter values $\mu-\varepsilon_1$ and $\mu+\varepsilon_2$, which are chosen from the available data to represent the range of reasonable values for the real cases.

The combined analysis, on the contrary, varies all parameters simultaneously and reveals the effects of parameter interaction on the model results. A factorial design approach is used for this purpose (Law and Kelton, 1991). For each of k parameters, two values are chosen and the model results are examined for all combinations (i.e., 2^k combinations) of these values. In this paper, the same $\mu-\varepsilon_1$ and $\mu+\varepsilon_2$ were used in both individual and combined analyses.

Two sensitivity measures are defined to assess the errors on the model results. The first measure is formulated to examine the maximum survival reduction (MSR) of the target model, and the second one is designed to investigate the flushing interval reduction (FIR). The definitions of these sensitivity measures are given in the following.

Table 1 Parameter values for sensitivity measure MSR

Parameter	Lower bound $\mu-\varepsilon_1$	Base value μ	Upper bound $\mu+\varepsilon_2$
d_s/D_g	0.03	0.07	0.11
h/L_1	0.2	0.5	0.8
L_2/L_1	15	35	55

3.1 Sensitivity measure for MSR

To examine the performance of embryo survival model under each parameter error, the index MSR is used, which is defined as the difference between the maximum and the minimum survival rates computed using sediment deposit σ and parameter values X listed in Table 1:

$$MSR(X) = S(\sigma_{\min}, X) - S(\sigma_{\max}, X) = S_{\max}(X) - S_{\min}(X) \quad (6)$$

Noted that survival rate S developed in the embryo survival model demonstrates a decreasing trend with increase of sediment deposit σ (Wu, 2000). Therefore, MSR can be also explained as the change of S when σ altered from its minimum to the maximum value. The sensitivity measure expressing the change in MSR from the base value would then be

$$SM_1(\mu+\varepsilon) = \frac{MSR(\mu+\varepsilon) - MSR(\mu)}{MSR(\mu)} \quad (7)$$

where $MSR(\mu)$ is defined as the base case index when the maximum survival reduction is computed using the base case parameter values, and $MSR(\mu+\varepsilon)$ is computed using either the lower or upper bound values.

For this measure, the analysis will be conducted on three model parameters, which are the ratio of sediment to gravel sizes d_s/D_g in (1), hydraulic pressure heads h/L_1 and intragravel flow path L_2/L_1 in (2). The parameter values selected to carry out the sensitivity analysis are summarized in Table 1, the details for determination of the parameter values can be found in Wu (2000).

Table 2 Parameter values for sensitivity measure FIR

Parameter	Lower bound $\mu - \varepsilon_1$	Base value μ	Upper bound $\mu + \varepsilon_2$
d_{10} / d_m	0.006	0.015	0.024
h / L_1	0.2	0.5	0.8
L_2 / L_1	15	35	55

3.2 Sensitivity measure for FIR

To investigate the effects of parameter errors on the flushing interval, the index FIR is used, which is defined as the change of flushing interval t_e between two different prescribed survival rates (herein from 75% to 80%) computed using parameter values X listed in Table 2:

$$FIR(X) = t_e(S = 75\%, X) - t_e(S = 80\%, X) \quad ....(8)$$

Noted that flushing interval t_e shortened with higher prescribed survival rate S (Wu, 2000). The choice for 75% and 80% of prescribed survival rate is empirical. However, it is considered appropriate to demonstrate the sensitivity analysis for the present study. The sensitivity measure expressing the change in FIR from the base value would then be

$$SM_2(\mu + \varepsilon) = \frac{FIR(\mu + \varepsilon) - FIR(\mu)}{FIR(\mu)} \quad ....(9)$$

where $FIR(\mu)$ is defined as the base case index when the flushing interval reduction is computed using the base case parameter values, and $FIR(\mu + \varepsilon)$ is computed using either the lower or upper bound values.

For this measure, the analysis will be conducted on three model parameters, i.e., d_{10} / d_m, h / L_1 and L_2 / L_1 in (5). The base values of the model parameters and their upper and lower bounds are determined through literature review (Wu, 2000). The parameter values for carrying out the sensitivity analysis are summarized in Table 2.

4. Results and Discussion

This section presents the results of sensitivity analysis on the target model. Results are presented

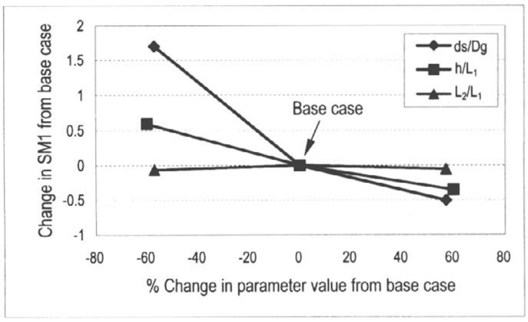

Figure 1 *MSR* sensitivity to changes in individual parameters

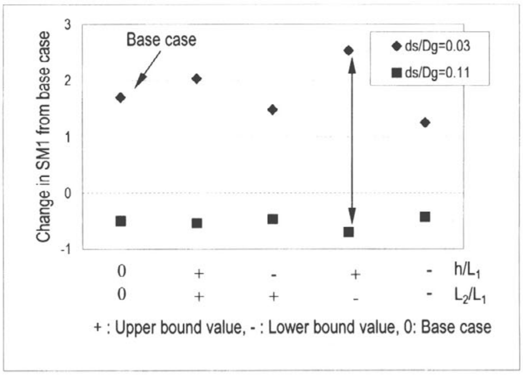

Figure 2 Combined effects of d_s/D_g on *MSR* sensitivity measure

separately for SM_1 and SM_2 in sections 4.1 and 4.2. An overall discussion of the results is given in section 4.3.

4.1 Results for SM_1

SM_1 measures the rate of change in maximum survival reduction, or MSR from the base value. $MSR(\mu)$ and $MSR(\mu + \varepsilon)$ are computed respectively for the base case, and for the cases using either the lower or upper bound values listed in Table 1. Results are presented below for both individual sensitivity analysis in Figure 1 and combined sensitivity analyses in Figures 2 to 4.

Figure 1 plots the results of individual analysis for SM_1, or MSR sensitivity to change in individual parameters. The horizontal axis represents the

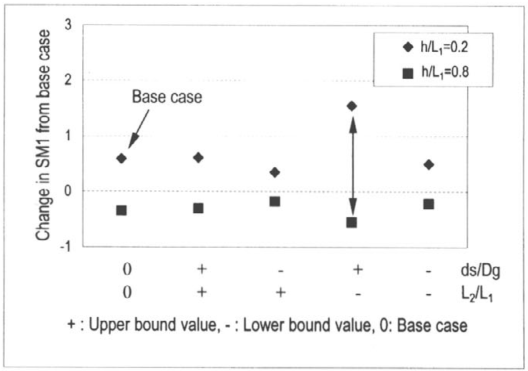

Figure 3 Combined effects of h/L_2 on *MSR* sensitivity measure

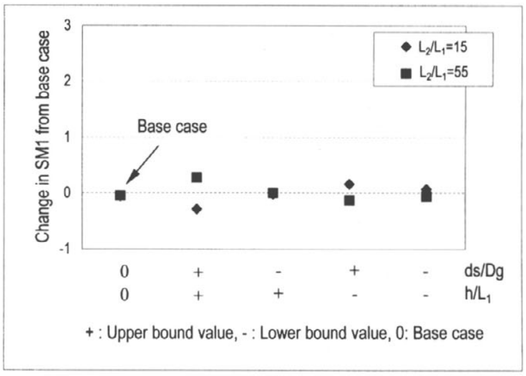

Figure 4 Combined effects of L_2/L_1 on *MSR* sensitivity measure

percentage of change in parameter value from the base value. For example, in Figure 1, both d_s/D_g and L_2/L_1 range from –57% to 57% of the base case value, while h/L_1 ranges from –60% to 60%. The vertical axis shows the change in SM_1 from the base case. The slope of each line represents the sensitivity of the target model to the parameter, the steeper the slope the more sensitive the model results are to that parameter. Figure 1 shows that the embryo survival model is most sensitive to decreases in d_s/D_g from its base value to its lower bound value. A 57% reduction in d_s/D_g results in a 1.7 increase in SM_1. Recall that SM_1 is defined as the rate of change in MSR from the base value, therefore, a 1.7 increase in SM_1 can be interpreted as 170% increase in MSR from the base value. Noted that the results of d_s/D_g are asymmetric, the model is more sensitive to the decreases in d_s/D_g than to the increases in d_s/D_g. A 57% increase in d_s/D_g only leads to a 0.51 decrease in SM_1. On the other hand, Figure 1 clearly shows that the slope of line L_2/L_1 between the lower and upper bound values is fairly small. The model is least sensitive to either increases or decreases in L_2/L_1 from its base value to its lower or upper bound value.

The results applying combined analysis for the three parameters are presented in Figures 2 to 4. The "vertical range" plot developed by Dosa (1994) is used for the presentation. For each parameter, two values (i.e., the upper and lower bound values) are selected and the model results are examined for all combinations of these values (i.e., 2^3 combinations). Figure 2 shows the combined effects of d_s/D_g on SM_1. The changes in SM_1 as d_s/D_g changed from its lower value of 0.03 to its upper value of 0.11 for each of the four combinations of the other parameters are plotted. For example, when h/L_1 is at its upper value (denoted by symbol "+") and L_2/L_1 at its lower value (denoted by symbol "–"), the value of SM_1 increases to 2.53 for lower value of d_s/D_g (57% reduction from the base value) and decreases to –0.7 for upper value of d_s/D_g (57% increase from the base value). The leftmost vertical line gives the results with h/L_1 and L_2/L_1 at their base case values for comparison. The length of the vertical line indicates the sensitivity of the model to the change of d_s/D_g for a particular combination of parameters. Figure 2 reveals that the value of d_s/D_g has a fairly significant effect on MSR for all combinations of h/L_1 and L_2/L_1, however, which is not true for the other parameters. Figure 3 shows the combined

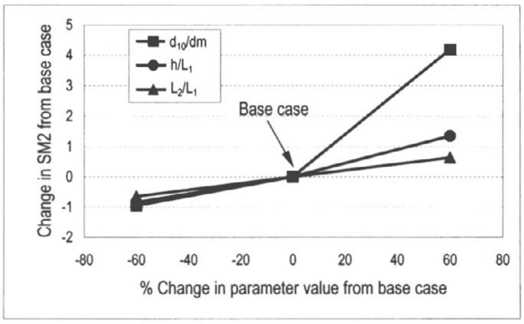

Figure 5 *FIR* sensitivity to changes in individual parameters

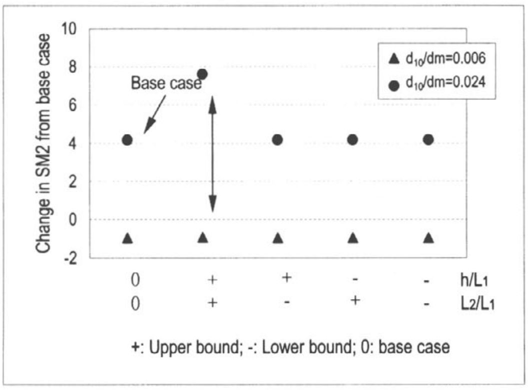

Figure 6 Combined effects of d_{10}/d_m on *FIR* sensitivity measure

effects of h/L_1 on SM_1. The varying lengths of the vertical lines indicate that the results of combined errors can be either more or less than those of individual errors in the h/L_1 values (i.e., base case errors). Compared to Figure 2, Figure 3 shows that except for the combination of d_s/D_g at its upper bound value and L_2/L_1 at its lower bound value, h/L_1 has much less effects on model results. However, Figure 4 clearly reveals that for all combinations of parameters, L_2/L_1 has little effect on the model results, which again confirms the results shown in Figure 1.

4.2 Results for SM_2

SM_2 measures the rate of reduction in the flushing interval, or FIR from the base value.

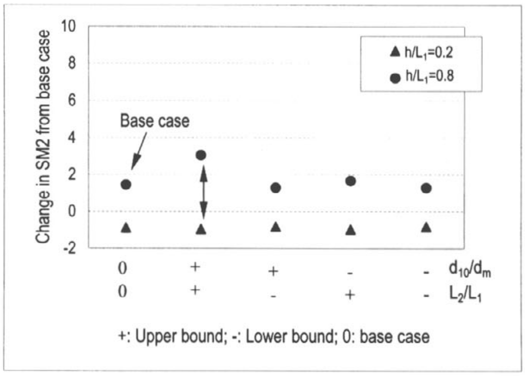

Figure 7 Combined effects of h/L_1 on *FIR* sensitivity measure

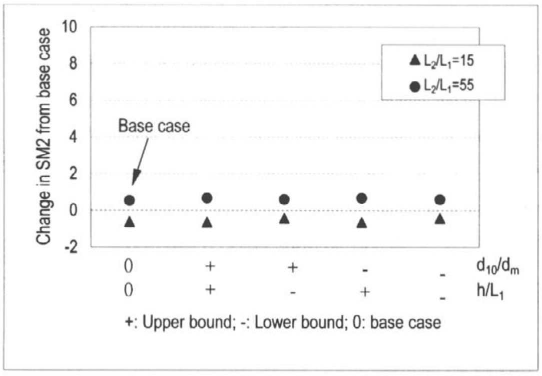

Figure 8 Combined effects of L_2/L_1 on *FIR* sensitivity measure

$FIR(\mu)$ and $FIR(\mu+\varepsilon)$ are computed respectively for the base case, and for the cases using either the lower or upper bound values listed in Table 2. Results are presented below for individual sensitivity analysis in Figure 5 and combined sensitivity analyses in Figures 6 to 8.

Figure 5 presents the results of individual analysis for SM_2, which shows the FIR sensitivity to changes in individual parameters. Again, the horizontal axis represents the percentage of change in parameter value from the base value, and the vertical axis shows the change in SM_2 from the base value. In this set of analysis, the ranges of all parameters fall within ±60% from their base values. Judging from the slopes of the lines, one realizes that the FIR is most sensitive to increases in

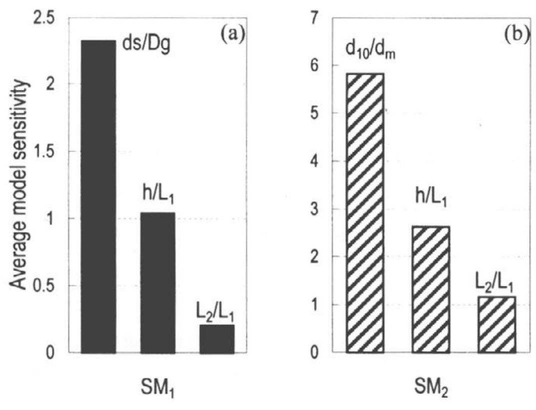

Figure 9　Average model sensitivity to changes in parameter values

d_{10}/d_m from its base value to its upper bound value. For example, a 60% increase in d_{10}/d_m results in a 4.2 increase in SM_2. Noted that the results of d_{10}/d_m are also asymmetric, the FIR is more sensitive to the increases than to the decreases in d_{10}/d_m. A 60% decrease in d_{10}/d_m ends up with less than 1.0 decrease in SM_2.

Figures 6 to 8 summarize the changes in SM_2 resulting from combined analysis for all three parameters. It is interesting to find from Figures 6 and 7 that the effect in one parameter is highly dependent on the combination of other parameters. The largest change in SM_2 occurs when d_{10}/d_m, h/L_1, and L_2/L_1 are all at their upper bound values. For example, in Figure 6, SM_2 reaches 7.6 compared to the 4.2 of the base case; in Figure 7, SM_2 reaches 3.0 compared to the 1.4 of the base case. Figure 6 also reveals that the value of d_{10}/d_m has the most significant effect on FIR for all combinations of h/L_1 and L_2/L_1 compared with other parameters. Figure 8 reconfirmed that model results are much less sensitive to L_2/L_1.

4.3 Overall Discussion

In this section, an overall discussion of the results on sensitivity analysis will be given. Figure 9 shows the average model sensitivity SM_1 and SM_2 to changes in parameter values from the lower bound to the upper bound values. For each of the three parameters, the average of the absolute values of the difference between the upper and lower bound for SM_1 and SM_2 are calculated. The absolute values are chosen to present model sensitivity because the changes in SM_1 and SM_2 could be either positive or negative, depending on the change in parameters. Figure 9(a) shows that SM_1 is most sensitive to the ratio of sediment to gravel sizes d_s/D_g, and followed by the hydraulic pressure heads h/L_1. The values examined in this study for the intragravel flow path L_2/L_1 are relatively small. Therefore, changes in L_2/L_1 will have little effects on model results. Recall that SM_1 is related to MSR, which is defined as the difference between the maximum and the minimum embryo survival rates. Figure 1 shows that a 57% reduction in d_s/D_g resulted in a 1.7 increase in SM_1, or a 170% increase in MSR. This implies that the decrease of sediment to gravel sizes ratio will substantially reduce the embryo survival rate. It can be also interpreted as that the errors in d_s/D_g are most likely to cause serious effects on model results (or embryo survival rate). It is worth mentioning that in Figure 2, d_s/D_g at its lower bound value has an even greater effect on SM_1 with a particular combination, i.e., h/L_1 at its upper bound value and L_2/L_1 at its lower bound value. Note that the data plotted in Figure 9 implicitly assume that each combination of the parameters is equally possible to occur. In fact, certain cases are more likely to occur than others.

Figure 9(b) shows the average model sensitivity SM_2 to changes in parameter values d_{10}/d_m, h/L_1, and L_2/L_1 from the lower bound to the upper bound values. It is presented in Figure 9(b) that d_{10}/d_m, or the characteristic parameter of sediment sizes has the greatest effect on SM_2, and followed by h/L_1. The intragravel flow path L_2/L_1 has the least effect on SM_2. Recall that SM_2 is related to FIR, which is defined as the change of flushing interval t_e between two different rescribed survival rates. Figure 5 indicates that a 60% increase in d_{10}/d_m resulted in a 4.2 increase in

SM_2, or a 420% increase in FIR. This implies that a minor increase in the characteristic parameter of sediment sizes will significantly increase the flushing frequency. It is also worth mentioning that, in Figure 6, d_{10} / d_m has a much greater effect on SM_2 when h / L_1 and L_2 / L_1 are both at their upper bound values.

5. Summary and Conclusions

Two sensitivity approaches are used in this paper to investigate the effects of parameter errors on the embryo survival rate and the interval between flushing flows: an individual analysis and a combined analysis. The following conclusions are drawn from this study:

(1)Individual analysis indicates that embryo survival is most sensitive to sediment-gravel size ratio, d_s / D_g. The results are more sensitive to the decreases in d_s / D_g and h / L_1 than to the increases in the two parameters. The model is least sensitive to the length of intragravel flow path, L_2 / L_1.

(2)Combined analysis indicates that the value of d_s / D_g has significant effects on embryo survival for all combinations of h / L_1 and L_2 / L_1. The lower bound value of d_s / D_g has an even greater effect on embryo survival when h / L_1 is at its upper bound value and L_2 / L_1 is at its lower bound value. The average model sensitivities to the changes in d_s / D_g, h / L_1, and L_2 / L_1 are 2.3, 1.1, and 0.2, respectively.

(3)Individual analysis indicates that flushing interval is most sensitive to d_{10} / d_m. The FIR is more sensitive to the increases than to the decreases in d_{10} / d_m. A 60% increase in d_{10} / d_m results in a 4.2 increase in SM_2. However, a 60% decrease in d_{10} / d_m ends up with less than 1.0 decrease in SM_2. The flushing interval is also least sensitive to the length of intragravel flow path, L_2 / L_1.

(4)Combined analysis indicates that d_{10} / d_m has significant effects on flushing interval for all combinations of h / L_1 and L_2 / L_1. The largest change in SM_2 occurs when d_{10} / d_m, h / L_1, and L_2 / L_1 are all at their upper bound values. The average sensitivities of FIR to d_{10} / d_m, h / L_1, and L_2 / L_1 are 5.8, 2.6, and 1.2, respectively.

The results of sensitivity analyses can serve as guidelines for restoration of spawning habitat and planning of flushing flows, they also provide insightful information that is useful for future uncertainty analysis.

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