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A MATHEMATICAL MODEL OF SALMONID SPAWNING HABITAT[1]

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ABSTRACT: A simulation model [Salmonid Spawning Analysis Model (SSAM)] was developed as a management tool to evaluate the relative impacts of stream sediment load and water temperature on salmonid egg survival. The model is useful for estimating acceptable sediment loads to spawning habitat that may result from upland development, such as logging and agriculture. Software in common use in the USA were adapted for use in gravel bedded rivers and linked to simulate water temperature (the USFWS Instream Water Temperature, SNTEMP model) and water and sediment routing (the USAE Scour and Deposition in Rivers and Reservoirs, HEC-6 model, version 3.2). These models drive the redd (spawning nest) model (the USDA-ARS Sediment Intrusion Dissolved Oxygen SIDO model) which simulates sediment intrusion and dissolved oxygen concentration in the redd environment. The SSAM model predictions of dissolved oxygen and water temperature compared favorably with field data from artificial redds containing hatchery chinook salmon eggs.
(KEY TERMS: salmonid; eggs; sediment intrusion; gravel; water quality; models.)

INTRODUCTION

Commercial and sport benefits resulting from anadromous fisheries averaged $434 million (U.S.) annually in the Pacific Northwest in the 1970s. Because of reduced anadromous fish populations, this value represents less than half the potential (Theurer, 1985). A large body of literature illustrates that fine sediment is detrimental to egg survival and developing embryos (Meehan and Swanston, 1977. Cooper, 1965; Chapman, 1988; Platts *et al.*, 1979; Iwamoto *et al.*, 1978). Major reasons for increases in fine sediment loading to spawning areas are agricultural development (Theurer, 1985) and forest harvesting and associated road building (Platts and Megahan, 1975).

This paper presents the results of a cooperative effort by the Agricultural Research Service and the Forest Service of the United States Department of Agriculture. With increased land and hydropower development, these agencies are concerned with the impacts of land management actions on instream sediment load and the effects on the spawning success of salmonid species. Previous studies on sediment intrusion into spawning gravels were predominantly site specific with limited geographical applicability. Because of the complexity of the environmental factors involved in salmonid egg survival, it became apparent that a simulation tool which was applicable to widespread geographic locations was desirable for the promotion of informed decisions regarding land development in areas upland of salmonid spawning habitat.

The Salmonid Spawning Analysis Model (SSAM) simulates the environmental variables controlling egg survival in the redd (spawning nest) habitat. Currently the chinook salmon and steelhead egg survival and fry emergence rates are simulated based on sediment particle size distribution, temperature, and dissolved oxygen in the redd. The following introductory remarks present some background on the effects of fine sediments in salmonid spawning habitat. Because stream sediment characteristics vary geographically, different sediment intrusion mechanisms were modeled. A short discussion of sediment intrusion mechanisms is followed by a synopsis of the mathematical models, an application of SSAM, and comparison of results with field data.

Salmonid species spawn in the gravels of freshwater streams. The nest, or redd, is a pocket of gravel

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from which the female has partially removed the sediment fines. Details of the redd construction process can be found elsewhere (Chapman, 1988). Large populations of spawners returning annually to a particular location serve to maintain a high quality spawning habitat. A large area of gravel cleaner than the surrounding stream substrate can develop in these areas (Chapman, 1988).

Fine material inevitably moves back into the redd environment after construction. The rate of movement depends on upstream sediment sources and stream discharge. The specific impacts on the developing embryos and fry depend on loading rates, particle size, and composition. Clays and silts cause low intragravel hydraulic conductivity, thereby reducing water flow and oxygen supply and the removal of metabolic waste products. Larger intruding particles (0.85 mm to 9.50 mm) may create a seal or clogged layer within the gravel framework preventing fry from emerging from the redd.

Sediment occurs in suspension over a wide range of flow rates. Intrusion rates of suspended sediment into porous gravels depend on the sediment concentration near the bed (Alonso and Mendoza, 1992) which may be several orders of magnitude higher than in the upper portions of the water column. Although not necessarily in constant suspension, fine sands may be transported across the stream substrate at relatively low flow rates. When the flow reaches a critical discharge in a gravel bedded river, the moveable bed portion of the stream substrate is set into motion carrying many size fractions from fine clays and silts to coarse gravels.

The impacts of fine and coarse sediment on redds varies because of different intrusion processes. Wash load material may fill the porous gravel framework from the bottom to the surface of the deposit. This intrusion mode was described by Einstein (1968) and was applied to spawning gravels by Alonso *et al.* (1988). However, the intrusion of coarser bed load material may result in the creation of a seal in the upper layers of the porous gravel deposit forming a barrier to deeper sediment intrusion. While adequate flow for egg survival may occur beneath the seal, fry may not be able to emerge through the sealed layer into the river environment. This intrusion mode has been studied theoretically (Lauck, 1991), in the laboratory (Beschta and Jackson, 1979; Diplas and Parker, 1985; Carling, 1984) and in the field (Frostick *et al.*, 1984; Havis, 1992; Lisle, 1989).

The simulation models employed in this study were developed to serve as management tools to analyze the relative effects of increased sedimentation from land management practices on salmonid spawning habitat. The models employ engineering approximations to provide reasonable predictions in an efficient computational environment. The purpose of this paper is to describe a model of salmonid spawning habitat and to compare simulations of redd water chemistry with redd habitat data from a field study site.

SALMONID SPAWNING ANALYSIS MODEL (SSAM)

The spawning habitat model consists of an ensemble of software packages which were linked to simulate water quality in the redd environment (Figure 1). The U.S. Army Corps of Engineers, Hydrologic Engineering Center's, Scour and Deposition in Rivers and Reservoirs model (HEC-6, Version 3.2, Hydrologic Engineering Center, 1977) is used to route sediment through a stream reach with spawning grounds. The U.S. Fish and Wildlife Service's Instream Water Temperature model (SNTEMP; Theurer *et al.*, 1984) uses solar and meteorological data to estimate water temperature, a variable used in HEC-6 calculations, and an important factor in egg survival. The SNTEMP model uses river width, estimated in HEC-6, for heat transport calculations. These two linked models exchange information on a daily time step. Output from these simulations are used to drive the U.S. Department of Agriculture Sediment Intrusion Dissolved Oxygen model (SIDO; Alonso *et al.*, 1988) in simulations of the redd environment.

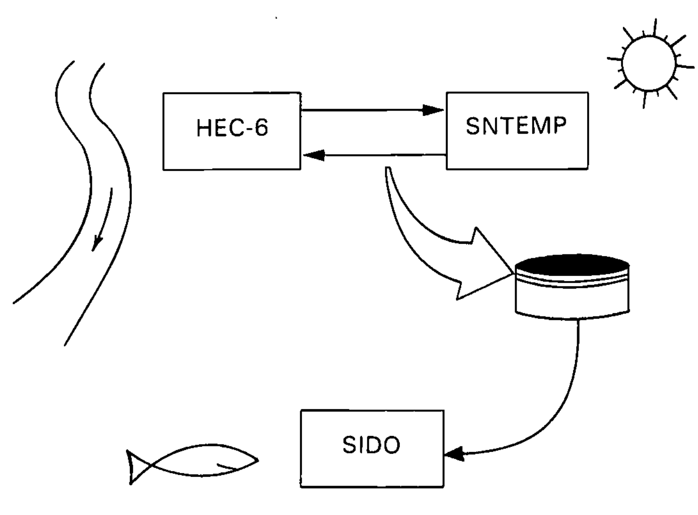

Figure 1. Flow Chart of the Salmonid Spawning Analysis Model (SSAM) Showing the Linkage of Model Components.

The HEC-6 model was originally developed to model sand bedded rivers and uses a one-dimensional flow, total-sediment load, computational scheme. Hence, several modifications were needed when applying the model to gravel bedded rivers having large lateral variability in flow and sediment transport [see Havis (1992) for details]. Cross sections were divided into subsections where geometry and hydraulic variables are calculated for each time step in the vicinity of spawning locations of interest. Suspended and bed load material were separated by comparing the settling velocities of each size fraction with the turbulent shear velocity. Many empirical relations show that sediment transport is a power function of stream flow with an exponent of about 2.0 (Knighton, 1980). Therefore, bed load was weighted laterally in the cross section, in proportion to the square of the subsection unit discharge. Using these approximations, the one-dimensional HEC-6 model was modified to simulate quasi two-dimensional flow and bed load sediment transport.

Through emulating lateral variability with a one-dimensional model, more precise estimates of sediment load and hydraulic geometry in the vicinity of the redd were achieved without excessive computational effort. The estimates of local water depths at individual redd sites allows more accurate calculation of the hydraulic pressure gradients that drive intragravel flow. The concentration of suspended load at the stream/gravel substrate interface is calculated based on the average suspended load concentration and the velocity profile (Alonso and Mendoza, 1992). The bed load sediment concentration is calculated on the basis of an average bed load particle velocity and expected range of motion with respect to the bed.

The reader is referred to documentation of the SIDO model (Alonso *et al.*, 1988) for a detailed mathematical description of the redd habitat. The redd domain was discretized for the purpose of solving the dispersion/advection equation which uses an alternating direction, implicit, finite difference method. A finite difference grid of 240 cells is used to represent the redd geometry in two dimensions (Alonso *et al.*, 1988). The redd domain is divided into four compartments: the upstream pit zone, the disturbed zone which overlays the egg pocket, the egg pocket, and the undisturbed stream substrate beneath the redd (Figure 2).

Sediment and dissolved oxygen are moved into the redd through advection and gravitational settling, neglecting the smaller dispersive transport mechanisms. The model simulates oxygen consumption by sediment, eggs, and alevins, and estimates fish survival based on the quantity and quality of intruding sediment and limiting values of dissolved oxygen and water temperature. Interstitial gravel velocities are

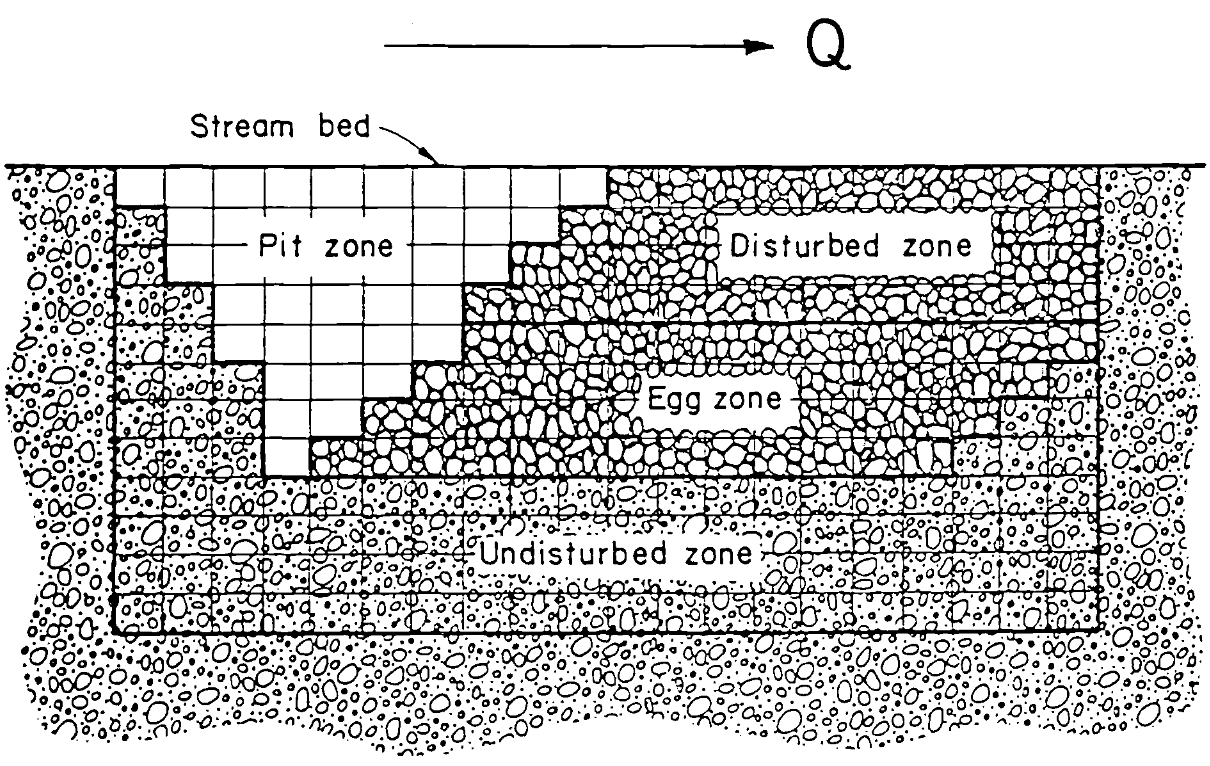

Figure 2. Discretized Redd Domain (from Alonso *et al.*, 1988).

calculated using a semi-empirical method based on particle size distributions (Alonso *et al.*, 1988). Fine sediment intrusion into the porous gravel framework follows the mechanisms described by Einstein (1968) when the geometric mean of the fines is less than $D_{50}^{f}/14$ (Sakthivadivel and Einstein, 1970). The term D_{50}^{f} refers to the particle diameter for which 50 percent of the framework particles are smaller. The criterium described by Diplas and Parker (1985), $5D_{15}^{s} < D_{15}^{f} < 5D_{85}^{s}$, was used to trigger seal development in the upper layers of the gravel deposit. The superscripts refer to intruding sediment (s), and the porous gravel framework (f), and the meaning of the subscripts were explained above. Sediment is deposited in the substrate by filtering and by gravitational settling. The sediment particle size distribution, porosity, hydraulic conductivity, interstitial velocity, dissolved oxygen concentration, oxygen demand rate, and blockage status of each finite difference cell is calculated for each time step.

MODEL EVALUATION

The SIDO model was initially developed for a site on the Tucannon River in southwestern Washington, USA (Alonso *et al.*, 1988). Sediment load in the Tucannon River is predominantly fine sands, silts, and clays. Model verification exercises showed that sediment intrusion by fine material was represented in a reasonable manner by SIDO. In agreement with field observations, filling of the redd gravel framework by fine sediment coincided with episodes of high flow and high suspended sediment load. To extend the model's capabilities to simulate sediment intrusion in streams with high sand loads, the model was modified to simulate intrusion of bed load material and the formation of seals as described above. The following sections illustrate the predicted effects of sediment intrusion from bed and suspended sediment load sources on the intragravel flow regime and water quality. Model simulations of water temperature and dissolved oxygen concentration were evaluated through comparisons with field data from the South Fork of the Salmon River in central Idaho.

Field Site

The South Fork of the Salmon River (SFSR) in central Idaho is part of the Columbia River system. Formed in the granitic material of the Idaho batholith, the river bed is rich in sands and gravels. Weathering of native granite in the central Idaho batholith produces sediment loads largely in the sand size class (0.062 to 2.0 mm, Dia.). The SFSR received high sand loading during the early 1960s because of the upland erosion of developed land during extreme climate events (Platts and Megahan, 1975) which impacted this important spawning and rearing habitat for anadromous fish. Significant improvement of the reach has been achieved since 1965 through a moratorium on timber harvesting and associated land development activities (Megahan *et al.*, 1980). However, cleansing of the gravel substrate may depend on future flushing flows (Platts *et al.*, 1989).

The reach under study is about 1.5 km long with bank-to-bank distances averaging about 30 meters (Figure 3). The channel cross section geometry was measured at 23 locations, and a gaging station was installed and monitored at the reach outlet and at the confluence of a tributary. Sediment routing calculations employed these flow measurements, as well as rating curves developed from suspended and bed load monitoring at the reach and tributary inlets and measurements of the stream substrate particle size distribution.

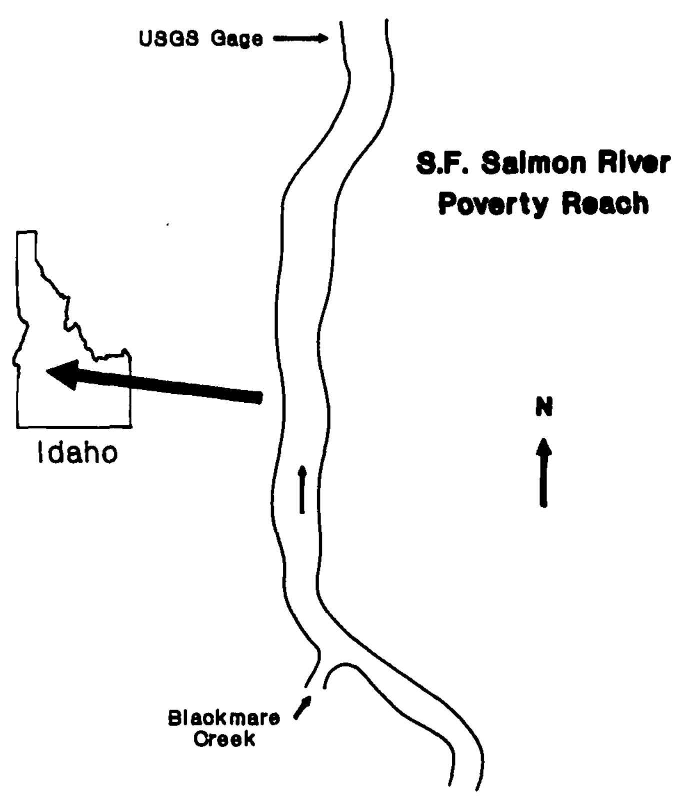

Figure 3. Location Map and Plan View of the Field Study Site. The reach is about 1.5 km long and bank-to-bank distance is about 30 meters.

The time of study, September 1990 to May 1991, represents the incubation period of chinook salmon eggs. This was a time of relatively low flow with a mean of 3.17 m^3/sec and a standard deviation of 2.44 m^3/sec. A field monitoring program designed to study sediment intrusion included flow and sediment measurements, the construction of artificial redds containing hatchery eggs, and the installation of intrusion buckets.

The following sections describe field measurements taken at the Poverty Reach study site and the application of SSAM. The SNTEMP model was verified by comparisons with temperature measurements taken at the water column/stream substrate interface. The HEC-6 model was evaluated by comparisons with water surface profile measurements and bed load and suspended load measurements which were taken at the reach inlet and outlet. The sediment intrusion model was calibrated using data from the intrusion bucket study. Measurements of water temperature and dissolved oxygen concentration in artificial redds containing chinook salmon eggs were used to evaluate simulations of water temperature and dissolved oxygen concentration.

Experimental Methods

River Mechanics. The HEC-6 model simulations employed the 23 cross sections where geometry was measured within Poverty Reach. The period of simulation for testing sediment routing calculations was the spring snowmelt hydrograph of 1990 (March 16 to July 31). Average daily flow rates and sediment load were measured on a tributary and daily flow and stage measurements were provided by a USGS gaging station at the reach outlet. Suspended sediment load was measured using a DH74 sampler, and bed load was measured using a Helley-Smith 3.25 in. sampler. Thirteen sediment load measurements at the upstream cross section were used to develop a total sediment load rating curve. The HEC-6 model simulations of sediment transport were compared to eight measurements of sediment transport at the reach outlet. In the sediment transport simulations, the initial bed gradation was estimated by a composite of three samples taken between 10 and 20 cm below the bed substrate surface.

Sediment Intrusion. Intrusion buckets (Lisle and Eads, 1991) were installed by excavating a 30 cm by 38 cm Dia. depression in the stream gravel substrate. A collapsed nylon bucket (40 cm by 30.5 cm Dia.) was placed in the depression and then filled with material larger than 6.35 mm. Chains, attached to the rim of the bucket, were left exposed on the substrate surface for later bucket removal and collection of the overlying material in the depression. At the end of the study period, the particle size distribution of the material less than 6.35 mm was measured to determine the total mass and size characteristics of the sediment intruding the porous gravel.

The intrusion buckets were installed on August 30, 1990, and collected on May 14, 1991, after 258 days of exposure to sediment intrusion under field conditions. The finite difference grid used to represent the redd domain in SIDO was modified to simulate the geometry of the intrusion bucket experiments. With identical initial framework grain sizes, the lower half was assigned to the egg zone and the upper half was assigned to the disturbed zone. Thus, the porous gravel framework, subject to sediment intrusion, was rectangular in two dimensions and had a flat surface.

Redd Environment. Artificial redds were constructed in the vicinity of natural redds within the study reach using the technique described by Burton *et al.* (1990). Hatchery chinook salmon eggs (n = 100) were inserted into the simulated egg pocket environment in each artificial redd. Simulations of the artificial redd environment employed particle size distributions in the egg pocket estimated by Platts *et al.* (1979) for Poverty Reach. The particle size distribution of the undisturbed zone was estimated in 1990 by sampling the substrate at a depth of 10 cm. The egg pocket was modeled having an egg count of 100 and dimensions characteristic of chinook salmon.

Water temperature and dissolved oxygen concentration were monitored through an access probe which was inserted into the vicinity of the artificial egg pocket during sampling. The probes consisted of a plastic well screen (approximately 5 cm Dia. and 30 cm long) with an access tube which extended to the stream substrate surface. Water samples were withdrawn, with a suction pump, from the egg pocket environment for temperature measurements and dissolved oxygen determination (Clesceri, 1989).

Results

River Mechanics. The HEC-6 model tended to overestimate total sediment transport during low flows and to underestimate sediment load at higher flows. Silt transport simulations showed similar trends to sand transport. The stream shear velocity method for separating bed and suspended sediment load was tested by comparison with HEC-6 simulations, using the Toffaleti transport capacity formula, and field measurements at the reach outlet (Table 1).

Total sediment load calculations compare favorably with field measurements having a maximum difference of approximately a factor of 2 (day 136).

Differences between measurements and predictions can be attributed to measurement errors and predictive uncertainties. Sources of experimental error included the nonsteady and nonuniform character of bed load movement and the short duration of sampling; the bed load sampler was placed on the bed for approximately one hour to obtain a sample. Model uncertainties include; the calculation of lateral bed load variability, variability in upstream sediment supply, sediment transport calculations, and the assumptions of uniform bed gradation at each cross section. Differences between measurement and simulation can be expected. Relatively large errors in predictions of bed load movement occurred on days 136 and 143 (Table 1), but there was surprisingly close agreement between measurements and predictions on all other sampling days.

Sediment Intrusion. Model simulations and field data are presented in terms of the fraction, by weight, of intruded material in a unit volume of substrate. This is the cumulative mass of sediment intruding the porous gravel framework divided by the original gravel framework mass. Under the relatively low flow regime of the study period, particle sizes in transport were too small to initiate sealing of the gravel interstices in the upper layers of the deposit. Hence, the intrusion mode described by Einstein (1968) prevailed.

The sediment intrusion model was calibrated using two constant variables: one to adjust the suspended load (Alonso *et al.*, 1988) and another to adjust bed load concentrations (Havis, 1992) at the boundary of the redd domain. Table 2 compares fractions of all material finer than 6.35 mm (total sediment) and material finer than 0.063 mm (silt and clay) measured in the intrusion bucket gravel samples to sediment intrusion simulations. In general agreement with field measurements, model predictions showed that a small portion of intruding sediment was associated with the wash load.

TABLE 2. The Measured and Simulated Fraction of Fines (mass fines/mass gravel framework) Intruding Into Individual Buckets Over the Study Period.

	Fraction Fines			
	Total		Silt and Clay	
Site	Measured	Simulated	Measured	Simulated
I-1	0.1402	0.0295	0.00209	0.00219
I-2	0.1454	0.0465	0.00239	0.00201
I-3	0.1094	0.0478	0.00168	0.00269
I-4	0.0794	0.0949	0.00103	0.00261
I-5	0.1485	0.1250	0.00232	0.00246
I-6	0.1458	0.0691	0.00299	0.00196
I-7	0.0577	0.1848	0.00388	0.00219
I-8	0.1338	0.2344	0.00169	0.00265
I-9	0.1636	0.1960	0.00305	0.00235
I-10	0.0585	0.1532	0.00269	0.00278
Mean	0.1182	0.1181	0.00238	0.00239
Std. Dev.	0.0395	0.0716	0.00082	0.00029

Although the rate of sediment intrusion could not be measured in the field because of the destructive nature of intrusion bucket sampling, model simulations provide probable trends. Ten sites in the lower part of the reach were simulated. The mean, predicted, cumulative total sediment intrusion is displayed by the dark line in Figure 4 along with the 95 percent confidence interval (light lines) and field measurement statistics (circle and bars). The increase in sediment intrusion rates during the last month of the study period was because of increased bed load rates associated with the beginning of the spring snowmelt hydrograph. Figure 5 shows that the effect of the spring snowmelt hydrograph on the intrusion pattern of the wash load was relatively small. As was shown

TABLE 1. Comparison of Sediment Load Measurements and Simulations at the Reach Outlet (tpd) Using the Modified HEC-6 Model.

Julian	Q	Total		Suspended		Bed	
Day	(m^3 s^{-1})	Measured	HEC-6	Measured	HEC-6	Measured	HEC-6
107	20.9	31.6	17.7	30.8	14.5	0.8	3.2
115	22.5	37.8	24.1	32.1	17.3	5.8	6.7
123	14.4	14.1	10.9	12.6	9.8	1.6	1.1
128	19.1	12.4	15.4	9.6	12.9	2.4	2.5
136	12.9	4.5	10.7	4.3	9.2	0.2	1.5
143	15.4	13.0	16.8	12.5	12.5	0.5	4.3
151	28.6	30.0	29.8	24.3	24.5	5.7	5.3
158	22.5	28.2	26.8	24.7	17.5	3.8	9.3

in the Tucannon River study (Alonso *et al.*, 1988), fine sediments have a significant impact on average intragravel flow velocities. Figure 6 shows the predicted mean, and 95 percent confidence interval, of the mean interstitial velocities calculated in the bottom half of the intrusion bucket domain.

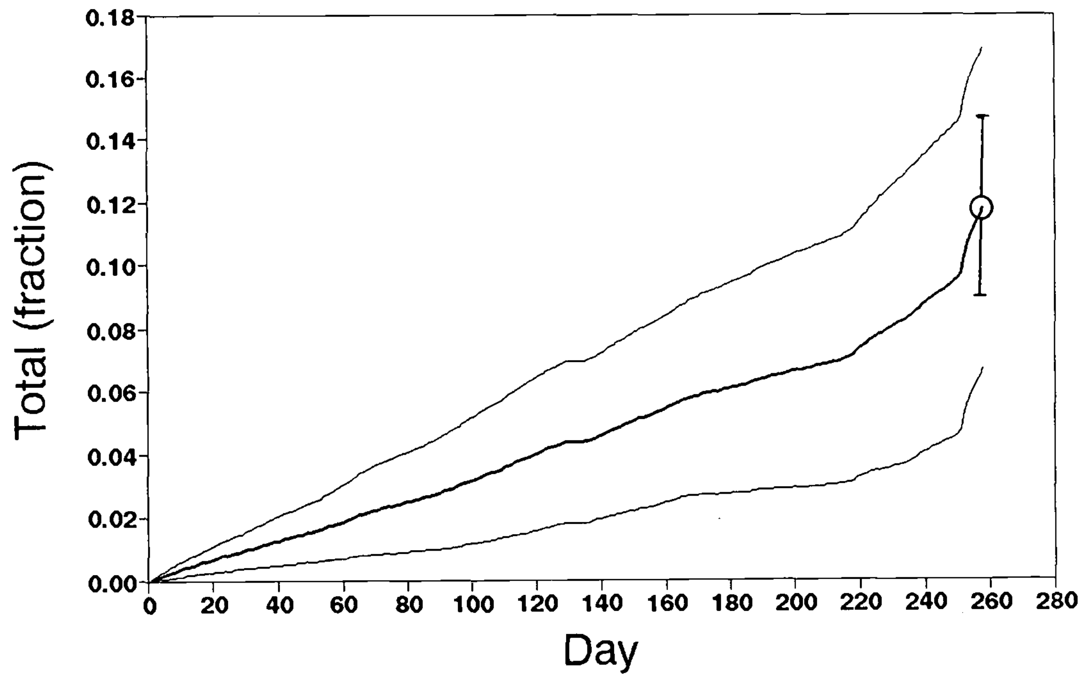

Figure 4. Predicted Mean and 95 Percent Confidence Interval of Total Cumulative Sediment Intrusion for 10 Sites in the Intrusion Bucket Study are Shown by Lines, and Measurements are Represented by the Circle (mean) and Bars (95 percent confidence interval).

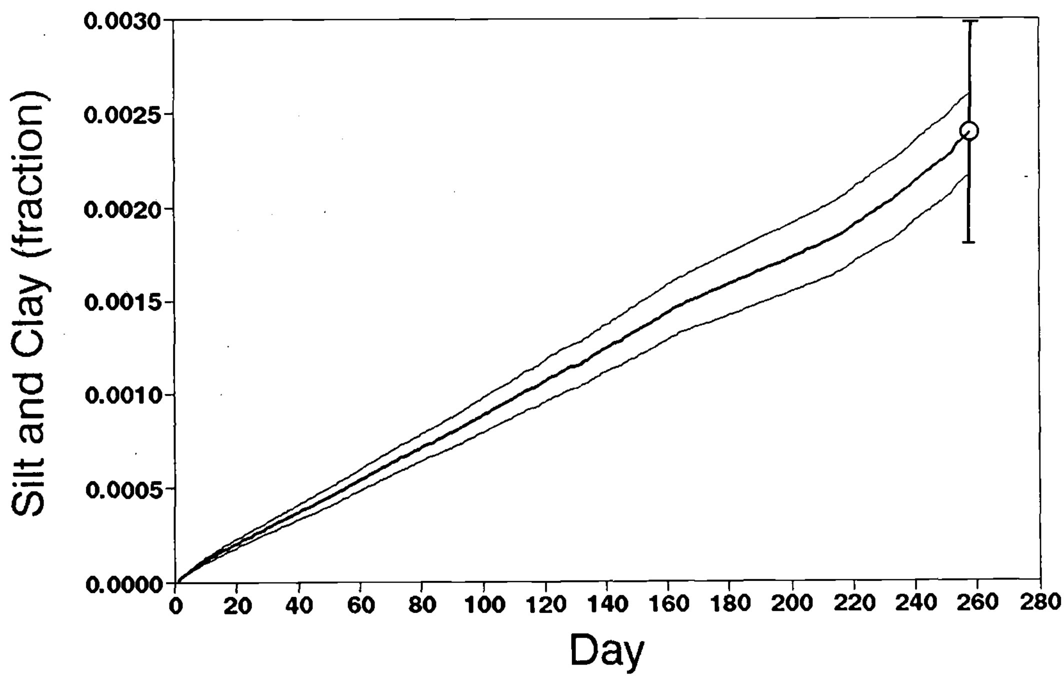

Figure 5. Predicted Mean and 95 Percent Confidence Interval of Cumulative Clay and Silt Sediment Intrusion for 10 Sites in the Intrusion Bucket Study are Shown by Lines, and Measurements are Represented by the Circle (mean) and Bars (95 percent confidence interval).

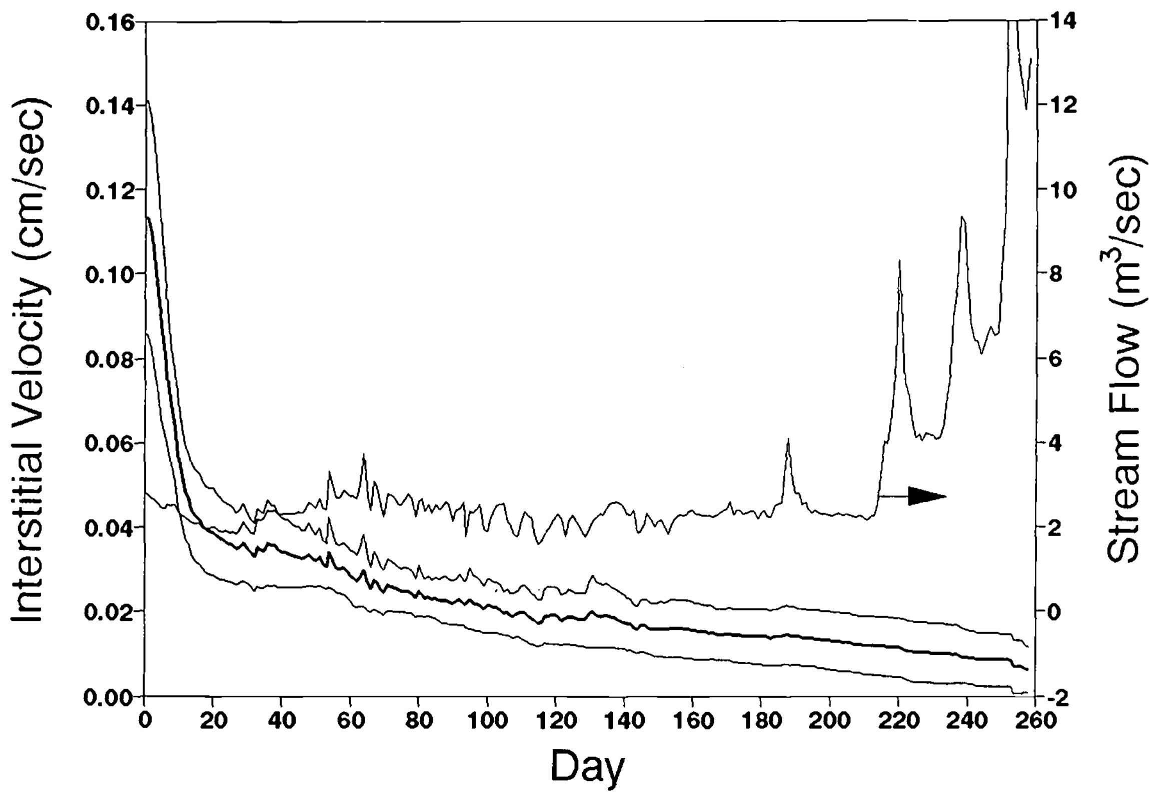

Figure 6. Predicted Mean and 95 Percent Confidence Interval of Interstitial Water Velocity in the Bottom Half of the 10 Intrusion Sites Studied. Interstitial velocity was calculated using a semi-empirical method based on particle size distribution. The measured stream flow during the study period is also shown.

A comparison of Figures 4 and 6 shows that, after 20 days, the predicted interstitial velocities in the bottom half of the intrusion buckets dropped by 65 percent in response to a 4 percent increase in the fraction of intruded fines. After the initial rapid drop, small fluctuations occurred in response to changes in flow rates (i.e., water surface profiles), which affected the hydrodynamic pressure gradients driving intragravel circulation. As the gravel was filled with intruding fines, towards the end of the study period, the mean predicted interstitial velocities in the lower portion of the computational domain appeared relatively insensitive to the rising limb of the spring hydrograph.

Redd Environment. Nondestructive sampling of the artificial redds was required in the study plan. Therefore, although sediment intrusion could not be directly measured, water temperature and dissolved oxygen data were recovered through the access probes. Ten artificial redds were simulated over the duration of the study period (August 30, 1990 to May 14, 1991). An example of model simulations of water temperature and dissolved oxygen concentration (Figure 7) shows good, overall agreement with field measurements. In the study area of relatively low organic loading to the aquatic environment and reduced sand erosion from managed forest lands, adequate oxygen was available to incubating eggs. Hence, measurements of dissolved oxygen concentrations appear to be chiefly influenced by water temperature.

SUMMARY AND CONCLUSIONS

Sediment loading from anthropogenic sources adversely affects salmonid spawning habitat by silting the porous gravel egg nest or redd. The Salmonid Spawning Analysis Model (SSAM) simulates the effects of gravel siltation on salmonid egg survival through considering sediment and water flow and temperature within a river reach. Within the redd environment, the model simulates sediment intrusion and particle size composition, interstitial velocities, and dissolved oxygen concentration (DO) including DO demand by sediment, as well as eggs. The user may use these results to estimate egg mortality caused by high water temperature or low rates of dissolved oxygen supply. Use of SSAM for land management requires estimates of the upstream sediment

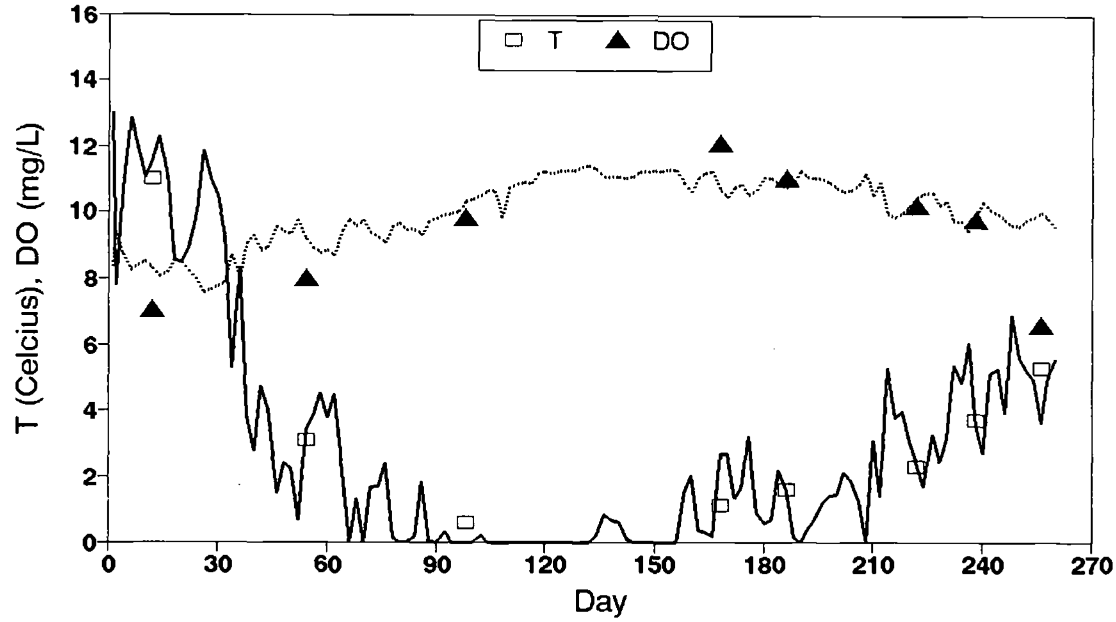

Figure 7. Model Simulations (lines) of Water Temperature and Dissolved Oxygen are Compared to Measurements (symbols) Taken in Artificial Redd Egg Pockets Containing Hatchery Eggs.

load resulting from a proposed land development action or program. The model could then be used to predict the relative impact of the resulting sediment load. Thus, for a desired percent fry emergence goal, an acceptable degree of upland development may be estimated.

Model comparisons with a field study program, using intrusion buckets, showed that the mean intruded sediment mass can be accurately represented through adjusting two calibration variables. One variable adjusts the bed load and another adjusts the suspended load concentration at the boundary of the redd domain. The importance of the intrusion of bed load material in the geography of the Idaho batholith was illustrated through measurements of intruding particle size distributions. While the intrusion rates could not be practically measured in the field, model simulations showed a reasonable intrusion pattern of suspended and bed load material. The calibrated model predicted dissolved oxygen concentration in artificial redds containing hatchery eggs with reasonable accuracy. The results presented here are preliminary, and further model testing at different geographical sites is necessary for further model verification.

Future laboratory scale mechanistic studies are needed to understand the process involved in seal formation as coarse sediment intrudes porous gravels. The mechanisms used to trigger seal development in SSAM (Havis, 1992) are rudimentary, but more detailed methods are computationally intensive. In addition to adequately representing mean sediment intrusion, the model provided a reasonable estimate of the variability shown by the field data. This variability in the simulations arises from the quasi two-dimensional representation of hydraulic geometry and bed load rates incorporated into the HEC-6 sediment routing methodology.

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