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An Alternative Approach for Assessing Sediment Impact on Aquatic Ecosystems Using Single Decision Tree (SDT)

Elfimov Valery Ivanovich, Khakzad Hamid*
[1] Division of Civil Engineering, Peoples' Friendship University of Russia, Moscow 117198

ABSTRACT

The purpose of this study was to identify factors affecting scale of the severity (SEV) of ill effect for fishes and to evaluate the derived prediction model. This study is based on 303 data about aquatic ecosystem quality over a wide range of sediment concentrations (1-500,000 mg SS/L) and durations of exposure (1-35,000 h). The independent variables were concentration of suspended sediment, species, life stage and duration of exposure. A single decision tree (SDT) analysis was done to identify factors for predicting a model of SEV and the CART algorithm was employed for building and evaluating regression trees. Results show that a single decision tree is better than traditional regression models with higher recognition rate and forecast accuracy and strong practical value.

Keywords: Scale of the severity; concentration of suspended sediment; species; life stage; duration of exposure; single decision tree

1. INTRODUCTION

The sudden release of large volumes of sediment may create serious problems downstream, such as, channel aggradations and flooding, interference with water supply and cooling water intakes, as well as adverse impacts on fisheries and the environment (Morris, 1995; Scheuerlein, 1995).

MacDonald and Newcombe (1993) grouped effects of suspended sediment on fish into three categories; lethal, sublethal and behavioral. These categories include the following:

Lethal effects kill individual fish, alter populations and decrease the capacity of fish to reproduce. They include sublethal and behavioral effects that give rise to reductions in population size.

Sublethal effects include tissue injury or changes in the physiology of an organism. The effect is chronic and may lead to an eventual decline in population size.

Behavioral effects are effects that result in any changes in activity normally associated with a species in an undisturbed environment, or associated with a species in an undisturbed environment. These changes may result in immediate death, or changes in population size or death over time.

Newcombe and Jensen (1996) developed a risk index and presented six regression equations for management decisions that relate biological response to duration of exposure and suspended sediment concentration. The equations all have the form: $z = a+b(\ln(x)+c(\ln(y))$, where, z is severity of ill effect, x is duration of

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**Corresponding to*: khakzad.hamid@yahoo.com
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exposure (h), y is concentration of suspended sediment (mg SS/L), a is the intercept, and b and c are slope coefficients. However, the study provided primary available estimates of the onset of sublethal and lethal effects, they applied regression models as a method to estimate SEV and have difficulties in showing the important factors affecting on SEV. In addition, it is likely that the assumptions that are made in a regression model may be violated in the case when the data of diseases or disorders are used in the model, because linear regression models need assumptions to be made, including assumptions about the linearity, normality, and homoscedasticity of the data among others (Byeon, 2014).

As mentioned before, the prediction of significant ill effect for fishes that is essentially an uncertain and random process is not easy to accomplish by using deterministic equations. Therefore, it is ideally suited to decision trees since they are primarily aimed at the recognition of a random pattern in a given set of input values. Decision trees are helpful in predicting the value of the output of a system from its corresponding random inputs as the application of decision trees does not require knowledge of the underlying physical process as a precondition. A single decision tree (SDT) analysis can be used both for classification and regression problems and has number of features, including ability to deal with collinear data, to exclude insignificant variables, and to allow asymmetrical distribution of samples (Coops et al., 2011). Examples of decision tree applications include potential profit analysis of water quality (Hao and Wen, 2010), earth observation and geoinformation (Haas and Ban, 2014), and an ecological risk assessment (Park et al., 2011). Chen and Mynett (2004) applied decision trees method into models construction to qualitatively predict Phaeocystisglobosa blooms in the Dutch coastal waters. Lu et al. (2009) used decision tree model to predict the level of chlorophyll in next day from Online Monitoring Station.

The present study develops and presents a new expert system to assess SEV as an indicator of ill effect for fishes using a single decision tree (SDT) model and results compared with linear regression models.

2. METHOD

2.1 Single decision trees

The patterns and relationships in data can be found using machine learning, statistical analysis, and other data mining techniques. Data mining takes advantage of advances in the fields of artificial intelligence (AI) and statistics. Both disciplines have been applied in pattern recognition and classification.

Decision trees are data mining methodologies applied in many real-world applications as a powerful solution to classification and prediction problems (Kantardzic, 2003). In the field of data mining, decision tree is a predictive model, a tree structure similar to the flowchart, which can help people to obtain a target value through the classification and analysis (Han et al., 2006).

In general, decision trees represent a disjunction of conjunctions of constraints on the attribute-values of instances. Each path from the tree root to a leaf corresponds to a conjunction of attribute tests and the tree itself to a disjunction of these conjunctions. More specifically, decision trees classify instances by sorting them down the tree from the root node to some leaf node, which provides the classification of the instance. Each node in the tree specifies a test of some attribute of the instance, and each branch descending from that node corresponds to one of the possible values for this attribute (Hand et al., 2001). The application of decision trees to classification was popularized in machine learning by Quinlan (1986). Quinlan's ID3 is a well-known tree-growing algorithm for generating decision trees based on univariate splits. An extended version of this algorithm, called C4.5 (Quinlan, 1993) and its successor C5.0 (Quinlan, 1998) use Greedy search methods. They involve growing and pruning decision-tree structures and are typically employed in these algorithms to explore the exponential space of possible models. The algorithm basically chooses the attribute that provides the maximum degree of discrimination between classes locally. Theoretical concepts related to decision trees can be found in many text books (Hand et al., 2001; Quinlan, 1986).

2.2 C5 algorithm

C5.0 is a commercial machine learning program developed by RuleQuest Research and is the successor of the widely used ID3 and C4.5 algorithms. A C5.0 decision tree is constructed using GainRatio. GainRatio is a measure incorporating entropy which measures how unordered the data set is. Entropy is denoted by the following equation:

$$\mathrm{Entropy}(S)=\sum_{i=1}^{N}-P(S_i)\log_2\left(P(S_i)\right) \tag{1}$$

where, $P(S_i)$ is the probability of class i occurring in the data set S and N is the number of classes. Using the *Entropy*, it is possible to calculate the Information Gain (Gain). Gain is a measure of the improvement in the amount of order given by:

$$\begin{gathered}\mathrm{Gain}(S,A)=\mathrm{Entropy}(S)-\sum_{V\in \mathrm{Value}(A)}\frac{|S_V|}{S}\times\mathrm{Entropy}(S_V),\\ S_V=\{s\in S|A(S)=V\}\end{gathered} \tag{2}$$

where $|S_V|$ and S are the number of data points in data sets SV and S, respectively and A is an attribute. Gain has a bias towards variables with many values that partition the data set into smaller ordered sets. In order to reduce this bias, the entropy of each variable over its m variable values is calculated as *SplitInformation*:

$$SplitInformation(S,A)=\sum_{i=1}^{m}-\frac{|S_i|}{|S|}\times\log_2\left(\frac{|S_i|}{S}\right) \tag{3}$$

Finally, *GainRatio* is calculated by dividing Gain by *SplitInformation* so that the bias towards variables with large value sets is dampened:

$$\mathrm{GainRatio}(S,A)=\frac{\mathrm{Gain(S,A)}}{\mathrm{SplitInformation}} \tag{4}$$

C5.0 builds a decision tree greedily by splitting the data on the variable that maximizes *Gain Ratio*.

2.3 CART algorithm

The Classification and Regression Trees (CART) method of Breiman et al. (1984) generates binary decision trees. CART is a non-parametric statistical methodology developed for analyzing classification issues either from categorical or continuous dependent variables. If the dependent variable is categorical, CART produces a classification tree. When the dependent variable is continuous, it produces a regression tree. The CART tree is constructed by splitting subsets of the data set using all predictor variables to create two child nodes repeatedly, beginning with the entire data set. The best predictor is chosen using a variety of impurity or diversity measures. The goal is to produce subsets of the data which are as homogeneous as possible with respect to the target variable. In the CART algorithm for each split, each predictor is evaluated to find the best cut point (continuous predictors) or groupings of categories (nominal and ordinal predictors) based on improvement score or reduction in impurity. Then the predictors are compared and the predictor with the best improvement is selected for the split. The process repeats recursively until one of the stopping rules is triggered. The process of constructing a regression tree is similar to that for building a classification tree. Regression tree building centers on three major components: (1) a set of questions of the form: is $X \leq d$? where X is a variable and d is a constant. As with the classification trees, the response to such questions is yes or no; (2) goodness of split criteria for choosing the best split on a variable, and (3) the generation of summary statistics for terminal nodes (unique to a regression tree). In regression tree, the least squared deviation (LSD) impurity measure is used for splitting rules and goodness of fit criteria. The LSD measure *R(t)* is simply the weighted within node variance for node *t*, and it is equal to the re-substitution estimate of risk for the node. It is defined as:

$$R(t) = \frac{1}{N_w(t)} \sum_{i \in t} w_i f_i (y_i - \bar{y}(t))^2 \qquad (5)$$

$$\bar{y}(t) = \frac{1}{N_w(t)} w_i f_i y_i \qquad (6)$$

$$N_w(t) = \sum_{i \in t} w_i f_i \qquad (7)$$

where $N_W(t)$ is the weighted number of records in node *t*, w_i is the value of the weighting field for record i (if any), f_i is the value of the frequency field (if any), y_i is the value of the target field, and $\bar{y}(t)$ is the mean of the dependent variable (target field) at node *t*. The LSD criterion function for split s at node *t* is defined as:

$$Q(S,T)=R(t)-R(t_L)-R(t_R) \qquad (8)$$

where, $R(t_R)$ is the sum of squares of the right child node and $R(t_L)$ is the sum of squares of the left child node. The split s is chosen to maximize the value of *Q(s,t)*. Stopping rules control how the algorithm decides when to stop splitting nodes in the tree. Tree growth proceeds until every leaf node in the tree triggers at least one stopping rule. Any of the following conditions will prevent a node from being split:

All records in the node have the same value for all predictor fields used by the model; The number of records in the node is less than the minimum parent node size (user defined); If the number of records in any of the child nodes resulting from the node's best split is less than the minimum child node size (user defined); The best split for the node yields a decrease in impurity that is less than the minimum change in impurity (user defined). In regression trees, each terminal node's predicted category is the $\bar{y}(t)$.

3. MATERIAL

3.1 Data set and experimental setup

In this study, we provide information (303 data) about aquatic ecosystem quality over a wide range of sediment concentrations, durations of exposure species, life stage and severity of ill effect for fishes (Table 1). Supporting data extracted from the review included taxonomic group, species of fish, natural history, life history phase, and sediment particle size range.

As before (MacDonald and Newcombe 1993; Newcombe, 1994) and in a nearly identical way, we scored qualitative response data along a semiquantitative ranking scale (Table 1). Superimposed on a 15-point scale (0-14) were four major classes of effect: (1) nil effect, (2) behavioral effects, (3) sub lethal effects (a category that also includes effects such as short-term reduction in feeding success), and (4) lethal effects (direct mortality, or its paralethal surrogates reduced growth, reduced Ash density, habitat damage such as reduced porosity of spawning gravel, delayed hatching, and reduction in population size). When these various effects could be compared directly, pollution episodes associated with sub lethal or lethal effects also degraded habitat and reduced population size, which is why these seemingly disparate ill effects are grouped together in the hierarchy. For events between the extremes of nil effect and 100% mortality, we assumed for modeling purposes that the severity-of-ill effects (SEV for "severity") scale represents proportional differences in true effects (Table 2). In this study, we define dose as concentration of suspended sediment (SS) times duration of exposure; dose has the unit of mg SS·h/L. Single decision tree (SDT), which is the basis of data presentation in this study, encompasses all combinations of sediment concentration (1-500,000 mg SS/L) and exposure duration (1-35,000 h). Except when it refers specifically to duration, we use "exposure" broadly to include dose, particle size, and other potential contributors to stress on fishes. In most cases, data on particle shape and roughness, and water temperature were lacking.

4. APPLICATION OF MODEL AND RESULTS

In this section of study, model were developed using a single decision tree analysis and these were compared against linear regression models. In the first step, the classification and regression tree (CART) algorithm was used to predict the related factors in the decision tree model. CART is an algorithm that performs a binary split, where only two child nodes are formed from the parent node. In the CART algorithm, the alpha value for the criteria of splitting and merging was set at 0.05. To make up for the imbalance in data distribution, the weights for misclassification costs were set asymmetrically. At the end of a training process, the model with the lowest error was selected as the final model. Statistical measures such as the Normalized mean square error (NMSE), the Correlation between actual and predicted, Root Mean Squared Error (RMSE) and Mean Absolute Percentage Error (MAPE) were employed for qualitative evaluation of the models. Fig. 1 shows the single decision tree diagrams and Table 3 shows the error statistics of calculated significant SEV by C5 and CART.

The information displayed in each node in Fig. 1 depends on whether it is a part of a classification tree (categorical target variable). Five lines of information are presented in this node: Node number - The top line displays the number of the node; Predictor variable used for split - The second line displays the name of the predictor variable that was used to generate the split from the parent node; Record counts - The “N=nn” shows how many rows (N) were placed in this node; The name of the target variable and the mean value of the target variable - The next-to-bottom line displays the name of the target variable (“SEV”) and the mean value of the target variable for all rows in this node; The standard deviation - The bottom line displays the standard deviation for the mean target value.

To find the relative importance of input parameters in decision trees the algorithm itself determines the important parameters through branching of inputs and knowledge of decision tree can help us choose parameters and assess the dependencies between related attributes. In this study, as can be seen, the greatest number of branching was performed using exposure duration. Therefore, exposure duration is the most important parameter for significant severity of ill effect for fishes prediction. Table 4 shows the relative importance of variables on SEV.

In the second step, when the analysis of the prediction model for SEV was completed, the results of the model compared with traditional regression models. The regression equations and correlation between actual and predicted values are (Newcombe, 1997);

$$\mathrm{SEV}=1.0642+0.6068\left(\ln\left(x\right)\right)+0.7384\left(\ln\left(y\right)\right),\quad R^2=0.6009;\ \text{For Juvenile and Adult salmonids} \tag{9}$$

$$\mathrm{SEV}=1.6814+0.4769\left(\ln\left(x\right)\right)+0.7565\left(\ln\left(y\right)\right),\quad R^2=0.6173;\ \text{For Adult salmonids} \tag{10}$$

$$\mathrm{SEV}=0.7262+0.7034(\ln(x))+0.7144(\ln(y)),\quad R^2=0.5984;\ \text{For Juvenile salmonids} \tag{11}$$

$$\mathrm{SEV}=3.7466+1.0946(\ln(x))+0.3117(\ln(y)),\quad R^2=0.5516;\ \text{For Eggs and Larvae} \tag{12}$$

$$\mathrm{SEV}=4.0815+0.7126(\ln(x))+0.2829(\ln(y)),\quad R^2=0.6998;\ \text{For Adult freshwater nosalmonids} \tag{13}$$

$$\mathrm{SEV}=3.4969+1.9647(\ln(x))+0.2669(\ln(y)),\quad R^2=0.6200;\ \text{For Adult estuarine nosalmonids} \tag{14}$$

Where, x is mg/l and y is hour. It can be seen that when compared the results generated by the decision tree with traditional regression models, the decision tree was more accurate with higher recognition rate and forecast accuracy and strong practical value in predicting the SEV (R^2=0.8003 for decision tree and R^2=0.6160 for traditional regression models in average).

In particular, the decision tree analysis not only can analyze nonparametric data but also is expressed by a tree structure for its analysis process, and the basis for prediction can be easily understood compared with the traditional regression models and the neural network or cluster analysis.

Table 1 Available data on the effects of suspended sediments on biota. Data take from the original literature

Species	**Life stage**	**Concentration (mg/L)**	**Exposure duration (h)**	**SEV**	**Fish response description**	**References**
Adult salmonids and rainbow smelt (freshwater, groups 1 and 2)						
Grayling (Arctic)	A	100.0	0.1	3	Fish avoided turbid water	Suchanek et al. (1984a, 1984b)
Grayling (Arctic}	A	100.0	1.008	8	Fish had decreased resistance to environmental stresses	McLeay et al. (1984)
Grayling (Arctic)	A	100.0	1.008	9	Impaired feeding	McLeay et al. (1984)
Grayling (Arctic)	A	100.0	1.008	9	Reduced growth	McLeay et al. (1984)
Salmon	A	25.0	4	4	Feeding activity reduced	Phillips (1970)
Salmon	A	16.5	24	4	Feeding behavior apparently reduced	Townsend (1983); Ott (1984)
Salmon	A	1650.0	240	7	Loss of habitat caused by excessive sediment transport	Coats et al. (1985)
Salmon	A	75.0	168	7	Reduced quality of rearing habitat	Slaney et al. (1977b)
Salmon	A	210.0	24	10	Fish abandoned their traditional spawning habitat	Hamilton (1961)
Salmon (Atlantic)	A	2500.0	24	10	Increased risk of predation	Gibson (1933)
Salmon (chinook)	A	650.0	168	5	No histological signs of damage to olfactory epithelium	Brannon et al. (1982)
Salmon (chinook)	A	350.0	0.17	7	Home water preference disrupted	Whitman et al. (1982)
Salmon (chinook)	A	650.0	168	7	Homing behavior normal, but fewer test fish returned	Whitman et al. (1982)
Salmon (chinook)	A	39300.0	24	10	No mortality	Newcomb and Flagg (1983)
Salmon (chinook)	A	82400.0	6	12	Mortality rate 60%	Newcomb and Flagg (1983)
Salmon (chinook)	A	207000.0	1	14	Mortality rate I00%	Newcomb and Flagg (1983)
Salmon (Pacific)	A	525.0	588	10	No mortality (other end points not investigated)	Griffin (1938)
Salmon (sockeye)	A	500.0	96	8	Plasma glucose levels increased 39%	Servizi and Martens (1987)
Salmon (sockeye)	A	1500.0	96	8	Plasma glucose levels increased 150%	Servizi and Martens (1987)
Salmon (sockeye)	A	39300.0	24	10	No mortality	Newcomb and Flagg (1983)
Salmon (sockeye)	A	82400.0	6	12	Mortality rate 60%	Newcomb and Flagg (1983)
Salmon (sockeye)	A	207000.0	1	14	Mortality rate 100% (VA)	Newcomb and Flagg (1983)
Smell (rainbow)	A	3.5	168	7	Increased vulnerability to predation	Swenson (1978)
Stcelhcad	A	500.0	3	5	Signs of sublethal stress (VA)	Redding and Schreck (1982)
Steelhead	A	16500.0	240	7	Loss of habit caused by excessive sediment transport	Coats et al. (1985)
Stcelhcad	A	500.0	9	8	Blood cell count and blood chemistry change	Redding and Schreck (1982)
Trout	A	16.5	24	4	Feeding behavior apparently reduced	Townsend (1983); Ott (1984)
Trout	A	75.0	168	7	Reduced quality of rearing habitat	Slaney et al. (1977b)

Species	Life stage	Concentration (mg/L)	Exposure duration (h)	SEV	Fish response description	References
Trout	A	270.0	312	8	Gill tissue damaged	Herbert and Merkens (1961)
Trout	A	525.0	588	10	No mortality (other end points not investigated)	Griffin (1938)
Trout	A	300.0	720	12	Decrease in population size	Peters (1967)
Trout (brook)	A	4.5	168	3	Fish more active and less dependent on cover	Gradatl and Swenson (1982)
Trout (brown)	A	1040.0	17520.0	8	Gill lamellae thickened	Herbert et al. (1961)
Trout (brown)	A	1210.0	17520	8	Some gill lamellae became fused (VFSS)	Herbert et al. (1961)
Trout (brown)	A	18.0	720	10	Abundance reduced	Peters (1967)
Trout (brown)	A	100.0	720	11	Population reduced	Scullion and Edwards (1980)
Trout (brown)	A	1040.0	8760	14	Population one-seventh of expected size (River Fal)	Herbert et al. (1961)
Trout (brown)	A	5838.0	8760	14	Fish numbers one-seventh of expected (River Par)	Herbert et al. (1961)
Trout (cutthroat)	A	35.0	2	4	Feeding ceased; fish sought cover	Cordone and Kelly (1961)
Trout (lake)	A	35.0	168	3	Fish avoided turbid areas	Swenson (1978)
Trout (rainbow)	A	66.0	1	3	Avoidance behavior manifested part of the lime	Lawrence and Scherer (1974)
Trout (rainbow)	A	665.0	1.0	3	Fish attracted to turbidity	Lawrence and Scherer (1974)
Trout (rainbow)	A	100.0	0.1	3	Fish avoided turbid water (avoidance behavior)	Suchanek et al. (1984a;1984b)
Trout (rainbow)	A	100.0	0.25	5	Rate of coughing increased (FSS)	Hughes (1975)
Trout (rainbow)	A	250.0	0.25	5	Rate of coughing increased (FSS)	Hughes (1975)
Trout (rainbow)	A	810.0	504	8	Gills of fish that survived had thickened epithelium	Herbert and Merkens (1961)
Trout (rainbow)	A	17500.0	168	8	Fish survived: gill epithelium proliferated and thickened	Slanina (1962)
Trout (rainbow)	A	50.0	960	9	Rate of weight gain reduced (CWS)	Herbert and Richards (1963)
Trout (rainbow)	A	50.0	960	9	Rate of weight gain reduced (WF)	Herbert and Richards (1963)
Trout (rainbow)	A	810.0	504	10	Some fish died	Herbert and Merkens (1961)
Trout (rainbow)	A	270.0	3240.0	10	Survival rate reduced	Herbert and Merkens (1961)
Trout (rainbow)	A	200.0	24	10	Test fish began to die on the first day (WF)	Herbert and Richards (1963)
Trout (rainbow)	A	80000.0	24	10	No mortality	D. Herbert, personal
Trout (rainbow)	A	18.0	720	10	Abundance reduced	Peters (1967)
Trout (rainbow)	A	59.0	2232	10	Habitat damage: reduced porosity of gravel	Slaney et al. (1977b)
Trout (rainbow)	A	4250.0	588	12	Mortality rate 50% (CS)	Herbert and Wakeford (1962)
Trout (rainbow)	A	49838.0	96	12	Mortality rate 50% (DM)	Lawrence und Scherer (1974)
Trout (rainbow)	A	3500.0	1488	13	Catastrophic reduction in population si/e	Herbert and Merkens (1961)
Trout (rainbow)	A	160000.0	24	14	Mortality rate 100%	D. Herbert, personal communication to Alabaster and Lloyd (1980)
Trout (sea)	A	210.0	24	10	Fish abandoned traditional spawning habitat	Hamilton (1961)
Whitefish (lake)	A	0.7	1.0	3	Swimming behavior changed	Lawrence and Scherer (1974)

Species	**Life stage**	**Concentration (mg/L)**	**Exposure duration (h)**	**SEV**	**Fish response description**	**References**
Whitefish (lake)	A	16613.0	96	12	Mortality rate 50% (DM)	Lawrence and Scherer (1974)
Whitefish (mountain)	A	10000.0	24.0	10.0	Fish died; silt-clogged gills Juvenile salmonids (freshwater, groups 1 and 3)	Langer (1980)
Juvenile salmonids (freshwater, groups 1 and 3)						
Grayling (Arctic)	U	20.0	24	3	Fish avoided parts of the stream	Birtwell et al. (1984)
Grayling (Arctic)	U	10000.0	96	3	Fish swam near the surface	McLeay et al. (1987)
Grayling (Arctic)	J	86.0	0.42	3	78% of fish avoided turbid water (NTU. >20)	Scannell (1988)
Grayling (Arctic)	U	100.0	1	4	Catch rate reduced (unfamiliar prey: drosophila)	McLeay et al. (1987)
Grayling (Arctic)	U	100.0	1	4	Catch rate reduced	McLeay et al. (1987)
Grayling (Arctic)	U	300.0	1	4	Catch rate reduced (unfamiliar prey: drosophila)	McLeay et al. (1987)
Grayling (Arctic)	U	1000.0	1	4	Feeding rate reduced	McLeay et al. (1987)
Grayling (Arctic)	U	1000.0	1	4	Feeding rate reduced (unfamiliar prey: drosophila)	McLeay et al. (1987)
Grayling (Arctic)	YY	3810.0	144	4	Food intake severely limited	Simmons (1982)
Grayling < Arctic)	U	100.0	12	6	Reduced ability to tolerate high temperatures	McLeay et al. (1987)
Grayling (Arctic)	U	100.0	756	7	Fish moved out of the test channel	McLeay et al. (1987)
Grayling (Arctic)	U	1000.0	1.008	8	Fish had frequent misstrikes while feeding	McLeay et al. (1987)
Grayling (Arctic)	U	1000.0	1.008	8	Fish responded very slowly to prey	McLeay et al. (1987)
Grayling (Arctic)	U	300.0	1.008	8	Rate of feeding reduced	McLeay et al. (1987)
Grayling (Arctic)	U	1000.0	840	8	Rate of feeding reduced	McLeay et al. (1987)
Grayling (Arctic)	U	1000.0	1.008	8	Fish failed to consume all prey	McLeay et al. (1987)
Grayling (Arctic)	U	300.0	840	8	Serious impairment of feeding behavior	McLeay et al. (1987)
Grayling (Arctic)	U	300.0	1.008	8	Respiration rate increased (FSS)	McLeay et al. (1987)
Grayling (Arctic)	U	300.0	1.008	8	Fish less tolerant of pentachlorophenol	McLeay et al. (1987)
Grayling (Arctic)	YY	3810.0	144	8	Mucus and sediment accumulated in the gill lamellae	Simmons (1982)
Grayling (Arctic)	YY	3810.0	144	8	Fish displayed many signs of poor condition	Simmons (1982)
Grayling (Arctic)	YY	1250.0	48	8	Moderate damage to gill tissue	Simmons (1982)
Grayling (Arctic)	YY	1388.0	96	8	Hyperplasia and hypertrophy of gill tissue	Simmons (1982)
Grayling (Arctic)	U	100.0	1.008	9	Growth rate reduced	McLeay et al. (1984)
Grayling (Arctic)	U	100.0	840	9	Fish responded less rapidly to drifting food	McLeay et al. (1987)
Grayling (Arctic!	U	300.0	1.008	9	Weight gain reduced	McLeay et al. (1987)
Grayling (Arctic)	U	1000.0	1.008	9	Weight gained reduced by 33%	McLeay et al. (1987)
Grayling (Arctic)	U	300.0	756	10	Fish displaced from their habitat	McLeay et al. (1987)
Grayling (Arctic)	U	100000.0	168	5	No changes in gill histology (not an end point)	McLeay et al. (1983)
Salmon (chinook)	S	943.0	72	8	Tolerance to stress reduced (VA)	Stober et al. (1981)
Salmon (chinook)	J	6.0	1440.0	9	Growth rate reduced (LNFH)	MacKinlcy et al. (1987)

Species	**Life stage**	**Concentration (mg/L)**	**Exposure duration (h)**	**SEV**	**Fish response description**	**References**
Salmon (chinook)	J	1400.0	36	12	Mortality rate 50%	Newcomb and Flagg (1983)
Salmon (chinook)	J	9400.0	36	12	Mortality rate 50%	Newcomb and Flagg (1983)
Salmon (chinook)	S	488.0	96	12	Mortality rate50%	Stober et al. (1981)
Salmon (chinook)	S	11000.0	96	12	Mortality rate 50%	Stober et al. (1981)
Salmon (chinook)	S	19364.0	96	12	Mortality rate 50%	Stober et al. (1981)
Salmon (chinook)	J	39400.0	36	14	Mortality rate 90% (VA)	Newcomb and Flagg (1983)
Salmon (chum)	J	28000.0	96.0	12	Mortality rate 50%	Smith (1940)
Salmon (chum)	J	55000.0	96.0	12	Mortality rate 50% (winter)	Smith (1940)
Salmon (coho)	J	53.5	0.02	1	Alarm reaction	Berg (1983)
Salmon (coho)	J	88.0	0.02	1	Alarm reaction	Bisson and Bilby (1982)
Salmon (coho)	U	20.0	0.05	1	Cough frequency not increased	Servizi and Martens (1992)
Salmon (coho)	J	53.5	12	3	Changes in territorial behavior	Berg and Northcote (2011)
Salmon (coho)	J	88.0	0.08	3	Avoidance behavior	Bisson and Bilby (1982)
Salmon (coho)	J	6000.0	1	3	Avoidance behavior	Noggle (1978)
Salmon (coho)	U	300.0	0.17	3	Avoidance behavior within minutes	Servizi and Martens (1992)
Salmon (coho)	J	25.0	1	4	Feeding rate decreased	Noggle (1978)
Salmon (coho)	J	100.0	1	4	Feeding rate decreased to 55% of maximum	Noggle (1978)
Salmon (coho)	J	250.0	1.0	4	Feeding rate decreased to 10% of maximum	Noggle (1978)
Salmon (coho)	J	300.0	1	4	Feeding ceased	Noggle (1978)
Salmon (coho)	U	2460.0	0.05	5	Coughing behavior manifest	Servizi and Martens (1992)
Salmon (coho)	J	53.5	12	6	Increased physiological stress	Berg and Northcote (2011)
Salmon (coho)	U	2460.0	1	6	Cough frequency greatly increased	Servizi and Martens (1992)
Salmon (coho)	U	240.0	24	6	Cough frequency increased more than 5-fold	Servizi and Martens (1992)
Salmon (coho)	U	530.0	96.0	6	Blood glucose levels increased	Servizi and Martens (1992)
Salmon (coho)	J	1547.0	96	8	Gill damage	Noggle (1978)
Salmon (coho)	U	2460.0	24	8	Fatigue of the cough reflex	Servizi and Martens (1992)
Salmon (coho)	U	3000.0	48	8	High level sublethal stress: avoidance	Servizi and Martens (1992)
Salmon (coho)	J	102.0	336	9	Growth rate reduced (FC. BC)	Sigler et al. (1984)
Salmon (coho)	U	8000.0	96.0	10	Mortality rate 1%	Servizi and Martens (1991)
Salmon (coho)	J	1200.0	96	12	Mortality rate 50%	Noggle (1978)
Salmon (coho)	J	35000.0	96	12	Mortality rate 50%	Noggle (1978)
Salmon (coho)	U	22700.0	96.0	12	Mortality rate 50%	Servizi and Martens (1991)
Salmon (coho)	F*	8100.0	96	12	Mortality rate 50%	Servizi and Martens (1991)
Salmon (coho)	PS	18672.0	96	12	Mortality rate 50%	Stober et al. (1981)
Salmon (coho)	S	509.0	96	12	Mortality rate 50%	Stober et al. (1981)
Salmon (coho)	S	1217.0	96	12	Mortality rate 50% (VA)	Stober et al. (1981)
Salmon (coho)	S	28184.0	96	12	Mortality rate 50% (VA)	Stober et al. (1981)
Salmon (coho)	S	29580.0	96	12	Mortality rate 50%	Stober et al. (1981)

Species	**Life stage**	**Concentration (mg/L)**	**Exposure duration (h)**	**SEV**	**Fish response description**	**References**
Salmon (sockeye)	S	1261.0	96	8	Body moisture content reduced	Servizi and Martens (1987)
Salmon (sockeye)	S	7447.0	96	8	Plasma chloride levels increased slightly	Servizi and Martens (1987)
Salmon (sockeye)	U	1465.0	96	8	Hypertrophy and necrosis of gill tissue (CSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	3143.0	96	8	Hypertrophy and necrosis of gill tissue (FSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	9851.0	96	8	Hypertrophy and necrosis of gill tissue (MCSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	17560.0	96.0	8	Hypertrophy of gill tissue (FSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	23790.0	96.0	8	Hypertrophy and necrosis of gill tissue (FSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	2688.0	96	8	Hypertrophy and necrosis of gill tissue (MCSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	2100.0	96	10	No fish died (MFSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	9000.0	96	10	No mortality	Servizi and Martens (1987)
Salmon (sockeye)	U	13900.0	96.0	10	Mortality rate 10% (FSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	9850.0	96	10	Gill hyperplasia, hypertrophy, separation, necrosis (MFSS)	Servizi and Martens (1987)
Salmon (sockeye)	J	1400.0	36	12	Mortality rate 50%	Newcomb and Flagg (1983)
Salmon (sockeye)	J	9400.0	36	12	Mortality rate 50%	Newcomb and Flagg (1983)
Salmon (sockeye)	U	1700.0	96	12	Mortality rate 50% (CSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	4850.0	96	12	Mortality rate 50% (MCSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	8200.0	96	12	Mortality rate 50% (MFSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	17560.0	96	12	Mortality rate 50% (FSS)	Servizi and Martens (1987)
Salmon (sockeye)	J	39400.0	36	14	Mortality rate 90% (VA)	Newcomb and Flagg (1983)
Salmon (sockeye)	U	13000.0	96	14	Mortality rate 90% (MFSS)	Servizi and Martens (1987)
Salmon (sockeye)	U	23900.0	96	14	Mortality rate 90% (FSS)	Servizi and Martens (1987)
Sieelhead	J	102.0	336	9	Growth rate reduced (FC. BC)	Sigler et al. (1984)
Trout (brook)	FF	12.0	5880.0	9	Growth rates declined	Sykora et al. (1972)
Troul (brook)	FF	24.0	5208.0	9	Growth rate reduced (LNFH)	Sykora et al. (1972)
Trout (brook)	FF*	100.0	1176.0	9	Test fish weighed 16% of controls (LNFH)	Sykora et al. (1972)
Trout (brook)	FF	50.0	1848	9	Growlh rates declined (LNFH)	Sykora et al. (1972)
Trout (rainbow)	FF	1750.0	480	12	Mortality rate 57% (controls 5%)	Campbell (1954)
Trout (rainbow)	J	4887.0	384	8	Hyperplasia of gill tissue	Goldes (1983)
Trout (rainbow)	J	4887.0	384	8	Parasitic infection of gill tissue	Goldes (1983)
Trout (rainbow)	J	171.0	96.0	8	Particles penetrated cells of branchial epithelium	Goldes (1983)
Troul (rainbow)	Y	90.0	456	10	Mortality rates 0-20% (DE)	Herbert and Merkens (1961)
Troul (rainbow)	Y	90.0	456	10	Mortality rates 0-15% (KC)	Herbert and Merkens (1961)
Trout (rainbow)	Y	270.0	456	11	Mortality rates 10-35% (KC)	Herbert and Merkens (1961)
Trout (rainbow)	Y	810.0	456	12	Mortality rates 35-85% (DE)	Herbert and Merkens (1961)
Trout (rainbow)	Y	810.0	456	12	Mortality rates 5-80% (KC)	Herbert and Merkens (1961)
Trout (rainbow)	Y	270.0	456	12	Mortality rates 25-80% (DE)	Herbert and Merkens (1961)
Trout (rainbow)	Y	7433.0	672	11.0	Mortality rate 40% (CS)	Herbert and Wakeford (1962)

Species	**Life stage**	**Concentration (mg/L)**	**Exposure duration (h)**	**SEV**	**Fish response description**	**References**
Trout (rainbow)	Y	4250.0	672	12	Mortality rate 50%	Herbert and Wakeford (1962)
Trout (rainbow)	Y	2120.0	672	14	Mortality rate 100%	Herbert and Wakeford (1962)
Troul (rainbow)	J	4315.0	57.0	14.0	Mortality rate -100* (CSS) Salmonid eggs and larvae (freshwater, group 4)	Newcombe et al. (1995)
Salmonid eggs and larvae (freshwater, group 4)						
Grayling (Arctic)	SF	25.0	24	10	Mortality rate 5.7%	J. LaPerriere (personal communication)
Grayling (Arctic)	SF	22.5	48	10	Mortality rate 14.0%	J. LaPerriere (personal communication)
Grayling (Arctic)	SF	65.0	24	10	Mortality rate 15.0%	J. LaPerriere (personal communication)
Grayling (Arctic)	SF	21.7	72	10	Mortality rate 14.7%	J. LaPerriere (personal communication)
Grayling (Arctic)	SF	20.0	96	10	Mortality rate 13.4%	J. LaPerriere (personal communication)
Grayling (Arctic)	SF	142.5	48	11.0	Mortality rate 26%	J. LaPerriere (personal communication)
Grayling (Arctic)	SF	185.0	72	12	Mortality rate 41.3%	J. LaPerriere (personal communication)
Grayling (Arctic)	SF	230.0	96	12	Mortality rate of 47%	J. LaPerriere (personal communication)
Salmon	E	117.0	960	10	Mortality: deterioration of spawning gravel	Cederholm et al. (1980)
Salmon (chum)	E	97.0	2808	13	Mortality rate 77% (controls. 6%)	Langer (1980)
Salmon (coho)	E	157.0	1728	14	Mortality rate 100% (controls. 16.2%)	Shaw and Maga (1943)
Steelhead	E	37.0	1488	12	Hatching success 42% (controls. 63%)	Sianey et al. (1977b)
Trout	E	117.0	960	10	Mortality; deterioration of spawning gravel	Cederholm et al. (1980)
Trout (rainbow)	EE	1750.0	144	10	Mortality rate greater than controls (controls. 6%)	Campbell (1954)
Trout (rainbow)	E	120.0	384	13	Mortality rates 60-70% (controls. 38.6%)	Erman and Lignon (1988)
Trout (rainbow)	E	101.0	1440.0	14.0	Mortality rate 98% (controls. 14.6%) Nonsalmonid eggs and larvae (estuarined, group 4)	TUrnpenny and Williams (1980)
Nonsalmonid eggs and larvae (estuarined, group 4)						
Bass (striped)	L	200.0	0.42	4	Feeding rate reduced 40%	Breitburg (1988)
Bass (striped)	E	800.0	24	9	Development rate slowed significantly	Morgan et al. (1983)
Bass (striped)	E	100.0	24	9	Hatching delayed	Schubel and Wang (1973)
Bass (striped)	E	1000.0	168	10	Reduced hatching success	Auld and Schubel (1978)
Bass (striped)	L	1000.0	68	11	Mortality rate 35% (controls. 16%)	Auld and Schubel (1978)

Species	**Life stage**	**Concentration (mg/L)**	**Exposure duration (h)**	**SEV**	**Fish response description**	**References**
Bass (striped)	L	500.0	72	12	Mortality rate 42% (controls. 17%)	Auld and Schubel*(*1978)
Bass (striped)	L	485.0	24	12	Mortality rate 50%	Morgan et al. (1973)
Herring	L	10.0	3	3	Depth preference changed	Johnson and Wildish (1982)
Herring (lake)	L	16.0	24	3	Depth preference changed	Swenson and Matson (1976)
Hemng (Pacific)	L	2000.0	2	4	Feeding rate reduced	Boehlert and Morgan (1985)
Herring (Pacific)	L	1000.0	24	8	Mechanical damage to epidermis	Boehlert (1984)
Herring (Pacific)	L	4000.0	24	8	Epidermis punctured: microridges less distinct	Boehlert (1984)
Perch (while)	E	800.0	24	9	Egg development slowed significantly	Morgan et al. (1983)
Perch (while)	E	100.0	24	9	Hatching delayed	Schubel and Wang (1973)
Perch (white)	E	1000.0	168	10	Reduced hatching success	Auld and Schubel (1978)
Perch (white)	L	155.0	48	12	Mortality rate 50%	Morgan et al. (1973)
Perch (white)	L	373.0	24	12	Mortality rate 50%	Morgan et al. (1973)
Perch (white)	L	280.0	48	12	Mortality rate 50%	Morgan et al. (1973)
Perch (yellow)	L	500.0	96	11	Mortality rate 37% (controls, 7%)	Auld and Schubel (1978)
Perch (yellow)	L	1000.0	96	11	Mortality rate 38% (controls, 7%)	Auld and Schubel (1978)
Shad (American)	L	100.0	96	10	Mortality rate 18% (controls, 5%)	Auld and Schubel (1978)
Shad (American)	L	500.0	96	11	Mortality rate 36% (controls, 4%)	Auld and Schubel (1978)
Shad (American)	L	1000.0	96.0	11.0	Mortality rate 34% (controls, 5%) (estuarine or riverine-estuarine, group 5) Adult nonsalmonids	Auld and Schubel (1978)
Adult nonsalinonids (estuarine or riverine-estuarine, group 5)						
Anchovy (bay)	A	231.0	24	10	Mortality rate 10% (FE)	Sherk et al. (1975)
Anchovy (bay)	A	471.0	24	12	Mortality rate 50% (FE)	Sherk et al. (1975)
Anchovy (bay)	A	960.0	24	14	Mortality rate 90%	Sherk et al. (1975)
Bass (striped)	A	1500.0	336	8	Haemalocrit increased (FE)	Sherk et al. (1975)
Bass (striped)	A	1500.0	336	8	Plasma osmolality increased (FE)	Sherk et al. (1975)
Cunner	A	28000.0	24	12	Mortality rate 50%	Rogers (1969)
Cunner	A	133000.0	12	12	Mortality rate 50% (15°C)	Rogers (1969)
Cunner	A	100000.0	24	12	Mortality rate 50% (15°C)	Rogers (1969)
Cunner	A	72000.0	48	12	Monality rate 50% (15°C)	Rogers (1969)
Fish	A	3000.0	240	10	Fish died	Kemp (1949)
Herring (Atlantic)	A	20.0	3	4	Reduced feeding rate	Johnson and Wildish (1982)
Hogchoker	A	1240.0	24	8	Energy utilization increased	Sherk et al. (1975)
Hogchoker	A	1240.0	120	8	Erythrocyte count increased	Sherk et al. (1975)
Hogchoker	A	1240.0	120	8	Haemalocrit increased	Sherk et al. (1975)
Killifish (striped)	A	960.0	120	8	Haemalocrit increased	Sherk et al. (1975)
Killifish (striped)	A	3277.0	24	10	Mortality rate 10% (FE)	Sherk et al. (1975)
Killifish (striped)	A	9720.0	24	10	Mortality rate 10%	Sherk et al. (1975)

Species	**Life stage**	**Concentration (mg/L)**	**Exposure duration (h)**	**SEV**	**Fish response description**	**References**
Killifish (striped)	A	3819.0	24	12	Mortality rate 50%	Sherk et al. (1975)
Killifish (striped)	A	12820.0	24	12	Mortality rate 50%	Sherk et al. (1975)
Killifish (striped)	A	16930.0	24	13	Mortality rate 90%	Sherk et al. (1975)
Killifish (striped)	A	6136.0	24	14	Mortality rate 90%	Sherk et al. (1975)
Menhaden (Atlantic)	A	154.0	24	10	Mortality rate 10% (FE)	Sherk et al. (1975)
Menhaden (Atlantic)	A	247.0	24	12	Mortality rate 50% (FE)	Sherk et al. (1975)
Menhaden (Atlantic)	A	396.0	24	14	Mortality rate 90% (FE)	Sherk et al. (1975)
Minnow (sheepshead)	A	200000.0	24	10	Mortality rate 10% (15°C)	Rogers (1969)
Minnow (sheepshead)	A	300000.0	24	11	Mortality rate 30% (10°C)	Rogers (1969)
Minnow (sheepshead)	A	100000.0	24	14	Mortality rate 90% (19°C)	Rogers (1969)
Mummichog	A	300000.0	24	10	No mortality (15°C)	Rogers (1969)
Mummichog	A	2447.0	24	10	Mortality rate 10% (FE)	Sherk et al. (1975)
Mummichog	A	3900.0	24	12	Mortality rate 50% (FE)	Sherk et al. (1975)
Mummichog	A	6217.0	24	14	Mortality rate 90%	Sherk et al. (1975)
Perch (white)	A	650.0	120	6	Haemalocrit increased	Sherk et al. (1975)
Perch (white)	A	650.0	120	6	Erythrocyte count increased	Sherk et al. (1975)
Perch (white)	A	650.0	120	6	Haemoglobin concentration increased	Sherk et al. (1975)
Perch (white)	A	305.0	120	8	Gill tissue may have been damaged	Sherk et al. (1975)
Perch (white)	A	650.0	120	8	Histological damage to gill tissue	Sherk et al. (1975)
Perch (white)	A	305.0	24	10	Mortality rate 10% (FE)	Sherk et al. (1975)
Perch (white)	A	985.0	24	12	Mortality rate 50%	Sherk et al. (1975)
Perch (white)	A	3181.0	24	14	Mortality rate 90% (FE)	Sherk et al. (1975)
Rasbora (harlequin)	A	40000.0	24	10	Fish died (BC)	Alabaster and Lloyd (1980)
Rasbora (harlequin)	A	6000.0	168	10	No mortality	Alabaster and Lloyd (1980)
Shad (American)	A	150.0	0.25	3	Change in preferred swimming depth	Dadswell et al. (1983)
Silverside (Atlantic)	A	58.0	24	10	Mortality rate 10% (FE)	Sherk et al. (1975)
Silverside (Atlantic)	A	250.0	24	12	Mortality rate 50% (FE)	Sherk et al. (1975)
Silverside (Atlantic)	A	1000.0	24	14	Mortality rate 90% (FE)	Sherk et al. (1975)
Spot	A	114.0	48	10	Mortality rate 10% (FE)	Sherk et al. (1975)
Spot	A	1309.0	24	10	Mortality rate 10% (FE)	Sherk et al. (1975)
Spot	A	6875.0	24	10	Mortality rate 10%	Sherk et al. (1975)
Spot	A	189.0	48	12	Mortality rate 50% (FE)	Sherk et al. (1975)
Spot	A	2034.0	24	12	Mortality rate 50%	Sherk et al. (1975)
Spot	A	8800.0	24	12	Mortality rate 50%	Sherk et al. (1975)
Spot	A	317.0	48	14	Mortality rate 90% (FE)	Sherk et al. (1975)

Species	**Life stage**	**Concentration (mg/L)**	**Exposure duration (h)**	**SEV**	**Fish response description**	**References**
Spot	A	11263.0	24	14	Mortality rate 90%	Sherk et al. (1975)
Stickleback (fourspine)	A	100.0	24	10	Mortality rate <1% (IA)	Rogers (1969)
Stickleback (fourspine)	A	10000.0	24	10	No mortality (KS; 10-12°C)	Rogers (1969)
Stickleback (fourspine)	A	300.0	24	12	Mortality rate ~50%	Rogers (1969)
Stickleback (fourspine)	A	18000.0	24	12	Mortality rate 50% (15.0-16.0°C)	Rogers (1969)
Stickleback (fourspine)	A	50000.0	24	12	Mortality rate 50% (KS)	Rogers (1969)
Stickleback (fourspine)	A	53000.0	24	12	Mortality rate 50% (10-12°C)	Rogers (1969)
Stickleback (fourspine)	A	330000.0	24	12	Mortality rate 50% (9.0-9.5°C)	Rogers (1969)
Stickleback (fourspine)	A	500.0	24	14	Mortality rate 100%	Rogers (1969)
Stickleback (fourspine)	A	200000.0	24	14	Mortality rate 95% (KS)	Rogers (1969)
Stickleback (threespine)	A	28000.0	96	10	No mortality in test designed to identify lethal threshold	LeGore and DesVoigne (1973)
Toadlish (oyster)	A	3360.0	1	6	Oxygen consumption more variable in prestressed fish	Neumann et al. (1975)
Toadlish (oysier)	A	14600.0	72	8	Fish largely unaffected, but developed latent ill effects	Neumann et al. (1975)
Toadlish (oyster)	A	11090.0	72.0	9.0	Latent ill effects manifested in subsequent test at low SS i (freshwater, group 6)	Neumann et al. (1975)
Bass (largemouth)	A	62.5	720	9	Weight gain reduced ~50%	Buck (1956)
Bass (largemouth)	A	144.5	720	9	Growth retarded	Buck (1956)
Bass (largemouth)	A	144.5	720	12	Fish unable to reproduce	Buck (1956)
Bluegill	A	423.0	0.05	4	Rate of feeding reduced	Gardner (1981)
Bluegill	A	15.0	1	4	Reduced capacity to locate prey	Vinyard and O'Brien (1976)
Bluegill	A	144.5	720	9	Growth retarded	Buck(1956)
Bluegill	A	62.5	720	9	Weight gain reduced ~50%	Buck (1956)
Bluegill	A	144.5	720	12	Fish unable to reproduce	Buck (1956)
Caф (common)	A	25000.0	336	10	Some mortality (MC)	Wallen (1951)
Darters	A	2045.0	8760	14	Darters absent	Vaughan (1979) Vaughan et al. (1982)

Species	**Life stage**	**Concentration (mg/L)**	**Exposure duration (h)**	**SEV**	**Fish response description**	**References**
Fish	A	120.0	384	10	Density of fish reduced	Erman and Lignon (1988)
Fish	A	620.0	48	10	Fish kills downstream from sediment source	Hesse and Newcomb (1982)
Fish	A	900.0	720	12	Fish absent or markedly reduced in abundance	Herbert and Richards (1963)
Fish	A	2045.0	8760.0	12	Habitat destruction: fish populations smaller than expected	Vaughan (1979) Vaughan et al. (1982)
Fish (warmwater)	A	100000.0	252	10	Some fish died: most survived	Wallen (1951)
Fish (warmwater)	A	200000.0	1.125	10	Fish died: opercular cavities and gill filaments clogged	Wallen (1951)
Fish (warmwater)	A	22.0	8760	12	Fish populations destroyed	Menzel et al. (1984)
Goldfish	A	25000.0	336	10	Some mortality (MC)	Wallen (1951)
Sunlish (green)	A	9600.0	1	5	Rate of ventilation increased	Horkel and Pearson (1976)
Sunlish (redear)	A	62.5	720	9	Weight gain reduced ~50% compared to controls	Buck (1956)
Sunfish (redear)	A	144.5	720	9	Growth retarded	Buck (1956)
Suntish (redear)	A	144.5	720	12	Fish unable to reproduce	Buck (1956)

: A = adult; E = egg; EE = eyed egg; F = fry; F = swim-up fry; FF = young fry (<30 weeks old); FF* = older fry (>30 weeks old); J = juvenile; L = larva; PS = presmolt; S = smolt; SF = sac fry; U = underyearling; Y = approximate yearling; YY = young of the year. As abbreviated here. VFSS = very fine; FSS = fine; MFSS = medium to fine; MCSS = medium to coarse; and CSS = coarse. Usual "sediments" used: BC = bentonite clay; CS =calcium sulfate; CWS = coal washery solids; DE = dtatomaceous earth; DM = drilling mud (nontoxic); FC = fire clay; FE = fuller's earth; IA = ncinerator ash; KC = kaolin clay; KS = Kingston silt; LNFH = lime-neutralized ferric hydroxide; MC = montmorillonite clay; VA = volcanic ash; WF = wood fibers, NTU= nephelometric turbidity units

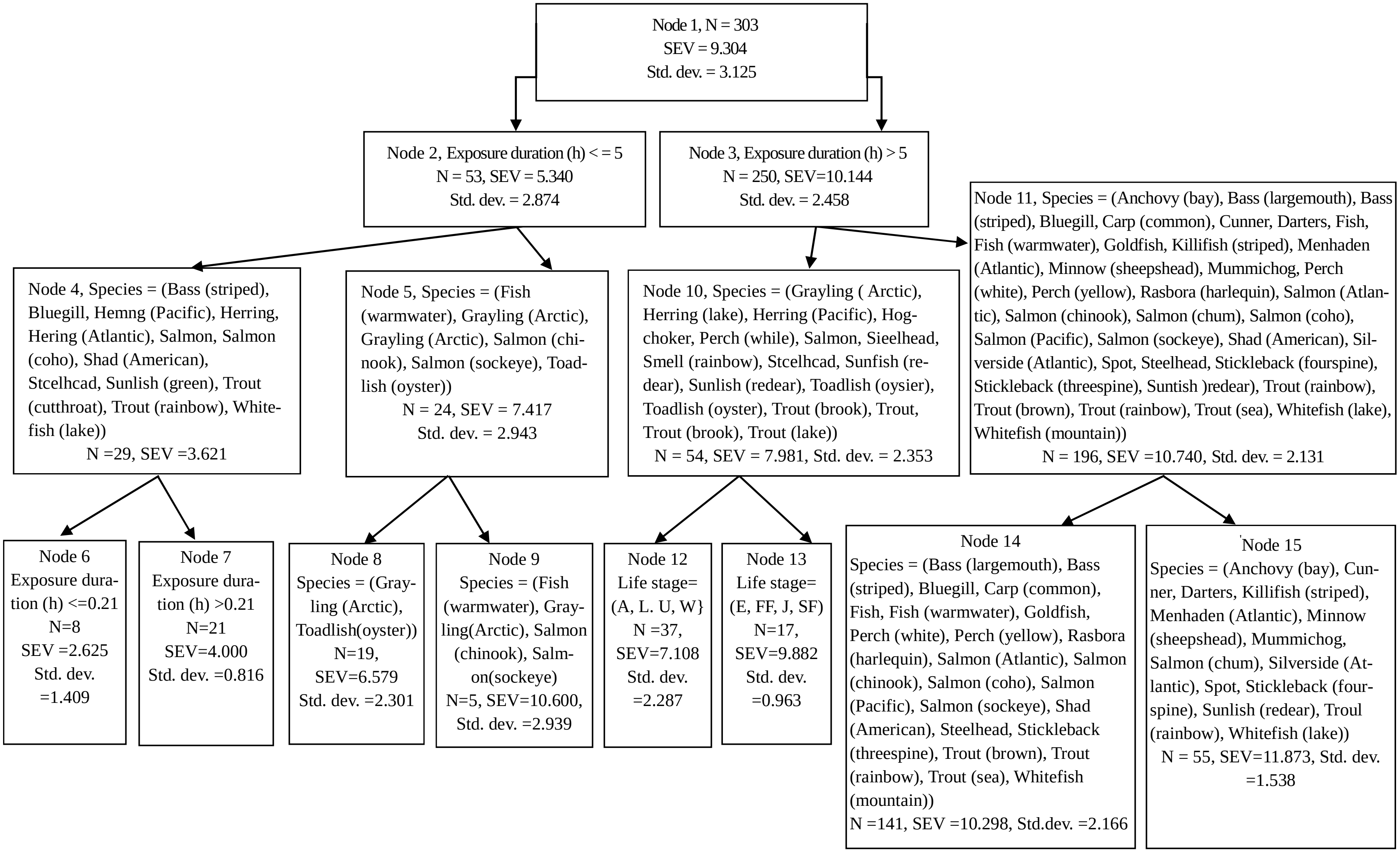

Figure 1 Single decision tree generated by CART algorithm

Table 2 Scale of the severity (SEV) of ill effects in fishes exposed to excess suspended sediment

Severity Index	Description of Effect
	Nil Effect
0	No behavioral Effect
	Behavioral Effects
1	Alarm reaction
2	Abandonment of cover
3	Avoidance response
	Sublethal Effects
4	Short-term reduction in feeding rate; short-term reduction in feeding success
5	Minor physiological stress; increase in rate of coughing; increased respiration rate
6	Moderate physiological stress
7	Moderate habitat degradation; impaired homing
8	Indications of major physiological stress; long-term reduction in feeding rate; long-term reduction in feeding success; poor condition
	Lethal and Paralethal Effects
9	Reduced growth rate; delayed hatching; reduced fish density
10	0-20% mortality; increased predation; moderate to severe habitat degradation
11	>20-40% mortality
12	>40-60% mortality
13	>60-80% mortality
14	>80-100% mortality

Table 3 Results of error statistics calculated SEV

Correlation between actual and predicted	0.800316
RMSE (Root Mean Squared Error)	1.892922
MAPE (Mean Absolute Percentage Error)	21.60838
Normalized mean square error (NMSE)	0.367029

Table 4 Relative importance of variables on SEV

Exposure duration (h)	100
Species	70.713
concentration (mg/L)	16.853
Life stage	14.463

SUMMARY AND CONCLUSIONS

A decision tree is a logical model represented as a binary tree that shows how the value of a target variable can be predicted by using the values of a set of predictor variables. In this study, a single decision tree (SDT) were used successfully for prediction of the scale of severity (SEV) based on concentration of suspended sediment, species, life stage and duration of exposure on the ill effect for fishes.

It was argued that in contrast with the traditional methods, decision trees represent rules; the algorithm itself determines the relative importance of parameters through branching of inputs. The results show that exposure duration and species are most important to SEV. In addition, decision trees have the advantage over traditional regression models in that they do not require parametric assumptions about the training data to be met, they can easily accommodate nonlinear relationships to outcome and are readily understood. We can use decision tree to make inferences that help us understand the "big picture" of the model.

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