Evaluation of effect of sediment on aquatic ecosystems using decision tree forest and group method of data handling

Hamid Khakzad and Valery Elfimov

ABSTRACT

In this study, the performances of the decision tree forest and group method of data handling for evaluation scale of the severity (SEV) of ill effect for fishes were investigated. The independent variables were concentration of suspended sediment (SS), species, life stage, and duration of exposure. This study is based on 198 data of aquatic ecosystem quality over a wide range of sediment concentrations (1–500,000 mg SS/L) and durations of exposure (1–35,000 h). Results showed that exposure duration is the most important factor on SEV, and based on the results, this alternative approach is better than traditional regression models with a higher recognition rate, forecast accuracy, and strong practical value.

Key words | concentration of suspended sediment, decision tree forest, group method of data handling duration of exposure, scale of the severity

Hamid Khakzad (corresponding author)
Valery Elfimov
Division of Civil Engineering,
Peoples' Friendship University of Russia,
Moscow 1171982,
Russia
E-mail: *khakzad.hamid@yahoo.com*

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 & Newcombe (1993) grouped effects of suspended sediment (SS) 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 change in activity normally 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 & Jensen (1996) developed a risk index and presented six regression equations for management decisions that relate biological response to duration of exposure and SS 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 exposure (h), y is concentration of SS (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 severity (SEV) and have difficulty in showing the important factors affecting 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,

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including assumptions about the linearity, normality, homoscedasticity of the data, etc. (Byeon 2014).

As mentioned above, 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 tree forest (DTF) and group method of data handling (GMDH) since they are primarily aimed at the recognition of a random pattern in a given set of input values. Decision tree forest and GMDH are helpful in predicting the value of the output of a system from its corresponding random inputs as the application of DTF and GMDH does not require knowledge of the underlying physical process as a precondition. In this study, DTF and GMDH were deployed to evaluate the impact of concentration of SS, species, life stage, and duration of exposure on a scale of the SEV of ill effect for fishes. This paper is prepared as follows. The next section describes the experimental setup and data set, followed by a section detailing DTF and GMDH, a section describing the results and statistical error analysis, and the final section provides a summary and conclusions.

MATERIAL

Data set and experimental setup

In this study, we provide information (198 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 previously (MacDonald & 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) sublethal 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 sublethal 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 SS times duration of exposure; dose has the units mg SS h L^{-1}. 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 on water temperature were lacking.

METHOD

Decision tree forest

A DTF can be used to evaluate the sensitivity of parameters or parameter combinations. A DTF is an ensemble of SDTs whose predictions are combined to make the overall prediction for the forest (Figure 1). In DTF, a large number of independent trees are grown in parallel, and they do not interact until after all of them have been built (Kunwar *et al*. 2013). Bootstrap resampling method (Efron 1979) and aggregating are the basis of bagging which is incorporated in DTF.

Different training subsets are drawn at random with replacement from the training data set. Separate models are produced and used to predict the entire data from the aforesaid subsets. Then, various estimated models are aggregated by using the mean for regression problems or majority voting for classification problems. Theoretically,

Table 1 | Available data on the effects of suspended sediments on biota

Species	Life stage	Concentration (mg/L)	Exposure duration (h)	SEV	Fish response description	Reference
Adult salmonids and rainbow smelt						
Grayling (Arctic)	A	100.0	0.1	3	Fish avoided turbid water	Suchanek *et al.* (1984a, b)
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 (personal communication)
Salmon	A	1,650.0	240	7	Loss of habit at caused by excessive sediment transport	Coats *et al.* (1985)
Salmon	A	75.0	168	7	Reduced quality of rearing habitat	Slaney *et al.* (1977)
Salmon	A	210.0	24	10	Fish abandoned their traditional spawning habitat	Hamilton (1961)
Salmon (Atlantic)	A	2,500.0	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.* (1981)
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	39,300.0	24	10	No mortality	Newcomb & Flagg (1983)
Salmon (chinook)	A	82,400.0	6	12	Mortality rate 60%	Newcomb & Flagg (1983)
Salmon (chinook)	A	207,000.0	1	14	Mortality rate I00%	Newcomb & 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		Servizi & Martens (1987)
Salmon (sockeye)	A	1,500.0	96	8		Servizi & Martens (1987)
Salmon (sockeye)	A	39,300.0	24	10	No mortality	Newcomb & Flagg (1983)
Salmon (sockeye)	A	82,400.0	6	12	Mortality rate 60%	Newcomb & 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 & Schreck (1982)
Steelhead	A	16,500.0	240	7	Loss of habitat caused by excessive sediment transport	Coats *et al.* (1985)
Steelhead	A	500.0	9	8	Blood cell count and blood chemistry change	Redding & Schreck (1982)
Trout	A	16.5	24	4	Feeding behavior apparently reduced	Townsend (1983); Ott (personal communication)
Trout	A	75.0	168	7	Reduced quality of rearing habitat	Slaney *et al.* (1977)
Trout	A	270.0	312	8	Gill tissue damaged	Herbert & Merkens (1961)

(*continued*)

Table 1 | continued

Species	Life stage	Concentration (mg/L)	Exposure duration (h)	SEV	Fish response description	Reference
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	Newcomb & Flagg (1983)
Trout (brook)	A	4.5	168	3	Fish more active and less dependent on cover	Newcomb & Flagg (1983)
Trout (brown)	A	18.0	720	10	Abundance reduced	Newcombe (1997)
Trout (cutthroat)	A	35.0	2	4	Feeding ceased; fish sought cover	Cordone & Kelley (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 time	Lawrence & Scherer (1974)
Trout (rainbow)	A	665.0	1	3	Fish attracted to turbidity	Lawrence & Scherer (1974)
Trout (rainbow)	A	100.0	0.1	3	Fish avoided turbid water (avoidance behavior)	Suchanek *et al.* (1984a, b)
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 & Merkens (1961)
Trout (rainbow)	A	17,500.0	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 & Richards (1963)
Trout (rainbow)	A	50.0	960	9	Rate of weight gain reduced (WF)	Herbert & Richards (1963)
Trout (rainbow)	A	810.0	504	10	Some fish died	Herbert & Merkens (1961)
Trout (rainbow)	A	270.0	3,240	10	Survival rate reduced	Herbert & Merkens (1961)
Trout (rainbow)	A	200.0	24	10	Test fish began to die on the first day (WF)	Herbert & Richards (1963)
Trout (rainbow)	A	80,000.0	24	10	No mortality	Herbert & Richards (1963)
Trout (rainbow)	A	18.0	720	10	Abundance reduced	Newcombe (1997)
Trout (rainbow)	A	59.0	2,232	10	Habitat damage: reduced porosity of gravel	Slaney *et al.* (1977)
Trout (rainbow)	A	4,250.0	588	12	Mortality rate 50% (CS)	Herbert & Wakeford (1962)
Trout (rainbow)	A	49,838.0	96	12	Mortality rate 50% (DM)	Lawrence & Scherer (1974)
Trout (sea)	A	210.0	24	10	Fish abandoned traditional spawning habitat	Hamilton (1961)
Whitefish (lake)	A	16,613.0	96	12	Mortality rate 50% (DM)	Lawrence & Scherer (1974)
Whitefish (mountain)	A	10,000.0	24.0	10	Fish died; silt-clogged gills juvenile salmonids	Langer (1980)
Juvenile salmonids						
Grayling (Arctic)	U	100.0	756	7	Fish moved out of the test channel	McLeay *et al.* (1987)
Grayling (Arctic)	U	1,000.0	1.008	8	Fish had frequent misstrikes while feeding	McLeay *et al.* (1987)
Grayling (Arctic)	U	1,000.0	1.008	8	Fish responded very slowly to prey	McLeay *et al.* (1987)

(*continued*)

Table 1 | continued

Species	Life stage	Concentration (mg/L)	Exposure duration (h)	SEV	Fish response description	Reference
Grayling (Arctic)	U	300.0	1.008	8	Rate of feeding reduced	McLeay *et al.* (1987)
Grayling (Arctic)	U	1,000.0	840	8	Rate of feeding reduced	McLeay *et al.* (1987)
Grayling (Arctic)	U	1,000.0	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	3,810.0	144	8	Mucus and sediment accumulated in the gill lamellae	Simmons (1982)
Grayling (Arctic)	YY	3,810.0	144	8	Fish displayed many signs of poor condition	Simmons (1982)
Grayling (Arctic)	YY	1,250.0	48	8	Moderate damage to gill tissue	Simmons (1982)
Grayling (Arctic)	YY	1,388.0	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	300.0	756	10	Fish displaced from their habitat	McLeay *et al.* (1987)
Salmon (chinook)	S	943.0	72	8	Tolerance to stress reduced (VA)	Stober *et al.* (1981)
Salmon (chinook)	J	6.0	1,440	9	Growth rate reduced (LNFH)	Newcomb & Flagg (1983)
Salmon (coho)	U	240.0	24	6	Cough frequency increased more than five-fold	Servizi & Martens (1992)
Salmon (coho)	J	1,547.0	96	8	Gill damage	Noggle (1978)
Salmon (coho)	U	2,460.0	24	8	Fatigue of the cough reflex	Servizi & Martens (1992)
Salmon (coho)	U	3,000.0	48	8	High level sublethal stress: avoidance	Servizi & Martens (1992)
Salmon (coho)	J	102.0	336	9	Growth rate reduced (FC. BC)	Sigler *et al.* (1984)
Salmon (coho)	U	8,000.0	96.0	10	Mortality rate 1%	Servizi & Martens (1991)
Salmon (coho)	J	35,000.0	96	12	Mortality rate 50%	Noggle (1978)
Salmon (coho)	U	22,700.0	96	12	Mortality rate 50%	Servizi & Martens (1991)
Salmon (coho)	F*	8,100.0	96	12	Mortality rate 50%	Servizi & Martens (1991)
Salmon (coho)	PS	18,672.0	96	12	Mortality rate 50%	Stober *et al.* (1981)
Salmon (coho)	S	28,184.0	96	12	Mortality rate 50% (VA)	Stober *et al.* (1981)
Salmon (coho)	S	29,580.0	96	12	Mortality rate 50%	Stober *et al.* (1981)
Salmon (sockeye)	S	1,261.0	96	8	Body moisture content reduced	Servizi & Martens (1987)
Salmon (sockeye)	U	1,465.0	96	8	Hypertrophy and necrosis of gill tissue (CSS)	Servizi & Martens (1987)
Salmon (sockeye)	U	3,143.0	96	8	Hypertrophy and necrosis of gill tissue (FSS)	Servizi & Martens (1987)
Salmon (sockeye)	U	2,688.0	96	8	Hypertrophy and necrosis of gill tissue (MCSS)	Servizi & Martens (1987)
Salmon (sockeye)	U	2,100.0	96	10	No fish died (MFSS)	Servizi & Martens (1987)
Salmon (sockeye)	U	9,000.0	96	10	No mortality	Servizi & Martens (1987)

(*continued*)

Table 1 | continued

Species	Life stage	Concentration (mg/L)	Exposure duration (h)	SEV	Fish response description	Reference
Salmon (sockeye)	U	13,900.0	96.0	10	Mortality rate 10% (FSS)	Servizi & Martens (1987)
Salmon (sockeye)	U	9,850.0	96	10	Gill hyperplasia, hypertrophy, separation, necrosis (MFSS)	Servizi & Martens (1987)
Salmon (sockeye)	J	9,400.0	36	12	Mortality rate 50%	Newcomb & Flagg (1983)
Salmon (sockeye)	U	8,200.0	96	12	Mortality rate 50% (MFSS)	Servizi & Martens (1987)
Salmon (sockeye)	U	17,560.0	96	12	Mortality rate 50% (FSS)	Servizi & Martens (1987)
Salmon (sockeye)	U	23,900.0	96	14	Mortality rate 90% (FSS)	Servizi & Martens (1987)
Sieelhead	J	102.0	336	9	Growth rate reduced (FC. BC)	Sigler *et al.* (1984)
Trout (brook)	FF*	100.0	1,176.0	9	Test fish weighed 16% of controls (LNFH)	Sykora *et al.* (1972)
Trout (brook)	FF	50.0	1,848	9	Growth rates declined (LNFH)	Sykora *et al.* (1972)
Trout (rainbow)	J	4,887.0	384	8	Hyperplasia of gill tissue	Goldes (1983)
Trout (rainbow)	J	4,887.0	384	8	Parasitic infection of gill tissue	Goldes (1983)
Trout (rainbow)	J	171.0	96.0	8		Goldes (1983)
Trout (rainbow)	Y	7,433.0	672	11	Mortality rate 40% (CS)	Herbert & Wakeford (1962)
Salmonid eggs and larvae						
Grayling (Arctic)	SF	25.0	24	10	Mortality rate 5.7%	Newcombe (1997)
Grayling (Arctic)	SF	22.5	48	10	Mortality rate 14.0%	Newcombe (1997)
Grayling (Arctic)	SF	65.0	24	10	Mortality rate 15.0%	Newcombe (1997)
Grayling (Arctic)	SF	21.7	72	10	Mortality rate 14.7%	Newcombe (1997)
Grayling (Arctic)	SF	20.0	96	10	Mortality rate 13.4%	Newcombe (1997)
Grayling (Arctic)	SF	142.5	48	11	Mortality rate 26%	Newcombe (1997)
Grayling (Arctic)	SF	185.0	72	12	Mortality rate 41.3%	Newcombe (1997)
Grayling (Arctic)	SF	230.0	96	12	Mortality rate 47%	Newcombe (1997)
Salmon (coho)	E	157.0	1,728	14	Mortality rate 100% (controls, 16.2%)	Shaw & Maga (1943)
Steelhead	E	37.0	1,488	12	Hatching success 42% (controls, 63%)	Newcombe (1997)
Trout (rainbow)	E	6.6	1,152	11	Mortality rate 40%	Newcomb & Flagg (1983)
Troul (rainbow)	E	57.0	1,488.0	12	Mortality rate 47% (controls, 32%)	Newcomb & Flagg (1983)
Trout (rainbow)	E	120.0	384	13	Mortality rates 60–70% (controls, 38.6%)	Erman & Lignon (1988)
Trout (rainbow)	E	20.8	1,152	13	Mortality rate 72%	Newcomb & Flagg (1983)
Troul (rainbow)	E	46.6	1,152	14	Mortality rate 100%	Newcombe (1997)
Trout (rainbow)	E	101.0	1,440	14	Mortality rate 98% (controls, 14.6%). Non-salmonid eggs and larvae (estuarine, group 4)	Turnpenny & Williams (1980)
Non-salmonid eggs and larvae						
Bass (striped)	E	800.0	24	9	Development rate slowed significantly	Morgan *et al.* (1983)
Bass (striped)	E	100.0	24	9	Hatching delayed	Newcombe (1997)
Bass (striped)	L	1,000.0	68	11	Mortality rate 35% (controls, 16%)	Auld & Schubel (1978)
Bass (striped)	L	500.0	72	12	Mortality rate 42% (controls, 17%)	Auld & Schubel (1978)
Bass (striped)	L	485.0	24	12	Mortality rate 50%	Morgan *et al.* (1973)

(*continued*)

Table 1 | continued

Species	Life stage	Concentration (mg/L)	Exposure duration (h)	SEV	Fish response description	Reference
Herring	L	10.0	3	3	Depth preference changed	Johnson & Wildish (1982)
Herring (lake)	L	16.0	24	3	Depth preference changed	Swenson & Matson (1976)
Hemng (Pacific)	L	2,000.0	2	4	Feeding rate reduced	Newcombe (1997)
Herring (Pacific)	L	1,000.0	24	8	Mechanical damage to epidermis	Newcombe (1997)
Perch (white)	E	800.0	24	9	Egg development slowed significantly	Morgan *et al.* (1983)
Perch (white)	E	100.0	24	9	Hatching delayed	Newcombe (1997)
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 & Schubel (1978)
Perch (yellow)	L	1,000.0	96	11	Mortality rate 38% (controls, 7%)	Auld & Schubel (1978)
Shad (American)	L	100.0	96	10	Mortality rate 18% (controls, 5%)	Auld & Schubel (1978)
Shad (American)	L	500.0	96	11	Mortality rate 36% (controls, 4%)	Auld & Schubel (1978)
Shad (American)	L	1,000.0	96	11	Mortality rate 34% (controls, 5%) (estuarine or riverine-estuarine, group 5). Adult non-salmonids	Auld & Schubel (1978)
Adult non-salinonids						
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)
Bass (striped)	A	1,500.0	336	8	Hematocrit increased (FE)	Sherk *et al.* (1975)
Bass (striped)	A	1,500.0	336	8	Plasma osmolality increased (FE)	Sherk *et al.* (1975)
Cunner	A	28,000.0	24	12	Mortality rate 50% (20.0–25.0 °C)	Rogers (1969)
Cunner	A	133,000.0	12	12	Mortality rate 50% (15 °C)	Rogers (1969)
Cunner	A	100,000.0	24	12	Mortality rate 50% (15 °C)	Rogers (1969)
Cunner	A	72,000.0	48	12	Monaliiy rale 50% (15 °C)	Rogers (1969)
Fish	A	3,000.0	240	10	Fish died	Kemp (1949)
Killifish (striped)	A	3,277.0	24	10	Mortality rate 10% (FE)	Sherk *et al.* (1975)
Killifish (striped)	A	3,819.0	24	12	Mortality rate 50%	Sherk *et al.* (1975)
Killifish (striped)	A	12,820.0	24	12	Mortality rate 50%	Sherk *et al.* (1975)
Killifish (striped)	A	16,930.0	24	13	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)
Minnow (sheepshead)	A	100,000.0	24	14	Mortality rate 90% (19 °C)	Rogers (1969)
Mummichog	A	2,447.0	24	10	Mortality rate 10% (FE)	Sherk *et al.* (1975)
Mummichog	A	3,900.0	24	12	Mortality rate 50% (FE)	Sherk *et al.* (1975)
Mummichog	A	6,217.0	24	14	Mortality rate 90%	Sherk *et al.* (1975)
Perch (white)	A	985.0	24	12	Mortality rate 50%	Sherk *et al.* (1975)

(*continued*)

Table 1 | continued

Species	Life stage	Concentration (mg/L)	Exposure duration (h)	SEV	Fish response description	Reference
Perch (white)	A	3,181.0	24	14	Mortality rate 90% (FE)	Sherk *et al.* (1975)
Rasbora (harlequin)	A	40,000.0	24	10	Fish died (BC)	Alabaster & Lloyd (1980)
Rasbora (harlequin)	A	6,000.0	168	10	No mortality	Alabaster & Lloyd (1980)
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	1,000.0	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	1,309.0	24	10	Mortality rate 10% (FE)	Sherk *et al.* (1975)
Spot	A	6,875.0	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	2,034.0	24	12	Mortality rate 50%	Sherk *et al.* (1975)
Spot	A	8,800.0	24	12	Mortality rate 50%	Sherk *et al.* (1975)
Spot	A	11,263.0	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	10,000.0	24	10	No mortality (KS; 10–12 °C)	Rogers (1969)
Stickleback (fourspine)	A	300.0	24	12	Mortality rate ~50% (IA)	Rogers (1969)
Stickleback (fourspine)	A	18,000.0	24	12	Mortality rate 50% (15.0–16.0 °C)	Rogers (1969)
Stickleback (fourspine)	A	53,000.0	24	12	Mortality rate 50% (10–12 °C)	Rogers (1969)
Stickleback (fourspine)	A	330,000.0	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 (threespine)	A	28,000.0	96	10	No mortality in test designed to identify lethal threshold	LeGore & DesVoigne (1973)
Toadlish (oyster)	A	14,600.0	72	8	Fish largely unaffected, but developed latent ill effects	Neumann *et al.* (1975)
Toadlish (oyster)	A	11,090.0	72	9	Latent ill effects manifested in subsequent test at low SS (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)
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)

(*continued*)

Table 1 | continued

Species	Life stage	Concentration (mg/L)	Exposure duration (h)	SEV	Fish response description	Reference
Carp (common)	A	25,000.0	336	10	Some mortality (MC)	Wallen (1951)
Fish	A	120.0	384	10	Density of fish reduced	Erman & Lignon (1988)
Fish	A	620.0	48	10	Fish kills downstream from sediment source	Hesse & Newcomb (1982)
Fish	A	900.0	720	12	Fish absent or markedly reduced in abundance	Herbert & Richards (1963)
Fish (warmwater)	A	100,000.0	252	10	Some fish died: most survived	Wallen (1951)
Fish (warmwater)	A	22.0	8,760	12	Fish populations destroyed	Newcombe (1997)
Goldfish	A	25,000.0	336	10	Some mortality (MC)	Wallen (1951)
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)

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; CSS = coarse. Usual 'sediments' used: BC = bentonite clay; CS = calcium sulfate; CWS = coal washery solids; DE = dtatomaceous earth; DM = drilling mud (non-toxic); FC = fire clay; FE = Fuller's earth; IA = incinerator 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.

in bagging, first a bootstrapped sample is constructed as (Erdal & Karakurt 2013)

$$D_i* = (Y_i*, X_i*) \tag{1}$$

where D_i* is a bootstrapped sample according to the empirical distribution of the pairs $D_i = (X_i,\ Y_i)$, where $(i = 1, 2, \ldots ; n)$. Second, the bootstrapped predictor is estimated by the plug-in principle

$$C_n*(x) = h_n(D_i*, \ \ldots, D_n*)(x) \tag{2}$$

where $C_n(x) = h_n(D_1, \ldots, D_n)(x)$ and h_n is the nth hypothesis. Finally, the bagged predictor is

$$C_{\mathrm{nB}}(x) = E*[D_n*(x)] \tag{3}$$

Bagging can reduce variance when combined with the base learner generation with a good performance. The DTFs gaining strength from bagging technique use the out of bag data rows for model validation. This provides an independent test set without requiring a separate data set or holding back rows from the tree construction. The stochastic element in DTF algorithm makes it highly resistant to over-fitting.

Statistical measures such as the coefficient of variation, the normalized mean square error (NMSE), the correlation between actual and predicted, root mean squared error (RMSE), and mean squared error were employed for qualitative evaluation of the models.

Group method of data handling

Group method of data handling is an evolutionary computation technique, which has a series of operations such as seeding, rearing, crossbreeding, and selection and rejection of seeds correspond to determination of the input variables, structure and parameters of the model, and selection of model by principle of termination (Ivahnenko 1971). In fact, the GMDH network is a very flexible algorithm, and it can be hybridized by using evolutionary and iterative algorithms such as genetic algorithm, genetic programming, particle swarm optimization, and back propagations. The previous researches established that hybridizations were successful in finding solutions of problems in different fields of engineering. By means of GMDH algorithm, a model can be represented as a set of neurons in which different pairs of them in each layer are connected through quadratic polynomials and thus produce new neurons in

Table 2 | Scale of the severity 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

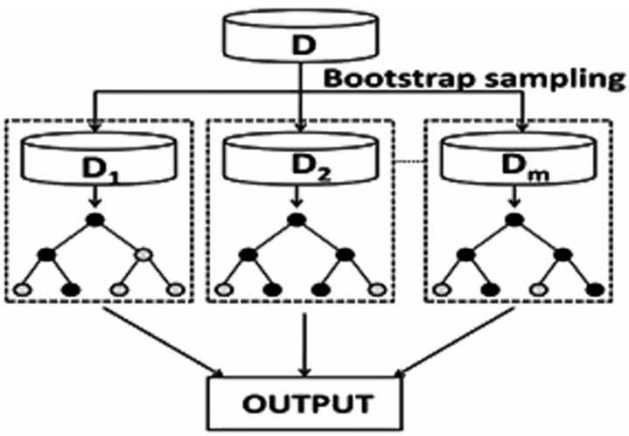

Figure 1 | Conceptual diagram of DTF.

the next layer. Such representation can be used in modeling to map inputs to outputs. The formal definition of system identification problem is to find a function $\hat{f}$ that can be used to approximate instead of actual function f, in order to predict the output $\hat{y}$ for a given input vector $X = (x_1, x_2, \ldots, x_n)$ as close as possible to its actual output y. Therefore, given n observation of multi-input single-output data pairs so that

$$y_i = f(x_{i1}, x_{i2}, x_{i3}, \ldots, x_{\text{in}}) \quad (i = 1, 2, \ldots .M) \tag{4}$$

It is now possible to train a GMDH network to predict the output values $\hat{y}_i$ for any given input vector $X = (x_{i1}, x_{i2}, \ldots, x_{\text{in}})$ that is

$$\hat{y}_i = \hat{f}(x_{i1}, x_{i2}, x_{i3}, \ldots, x_{\text{in}}) \quad (i = 1, 2, \ldots, M) \tag{5}$$

The problem is now to determine a GMDH network so that the square of difference between the actual output and the predicted one is minimized, that is,

$$\sum_{i=1}^{M} \left[\hat{f}(x_{i1}, x_{i2}, x_{i3}, \ldots, x_{\text{in}}) - y_i\right]^2 \rightarrow \min \tag{6}$$

General connection between inputs and output variables can be expressed by a complicated discrete form of the Volterra function, a series in the form of

$$y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij} x_i x_j + \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n} a_{ijk} x_i x_j x_k \tag{7}$$

which is known as the Kolmogorov–Gabor polynomial (Farlow 1984). The polynomial order of PDs is the same in each layer of the network. In this scenario, the order of the polynomial of each neuron is maintained across the entire network. For example, assume that the polynomials of the neurons located at the first layer are those of the second order (quadratic)

$$\hat{y} = G(x_i, x_j) = a_0 + a_1 x_i + a_2 x_j + a_3 x_i x_j + a_4 x_i^2 + a_5 x_j^2 \tag{8}$$

Here, all polynomials of the neurons of each layer of the network are the same, and the design of the network is

based on the same procedure. The second-order polynomial is the fundamental structure of the GMDH network that has been proposed by Ivahnenko. Generally, different types of polynomial such as bilinear, quadratic, triquadratic, and third order are used to design self-organized systems. The use of triquadratic and third-order polynomials can generate more complicated networks in comparison with quadratic polynomials. Bilinear polynomials produce lower complicated structures in comparison with quadratic polynomials. A quadratic polynomial has six weighting coefficients that have generated good results in engineering problems. Based on the previous investigations, the selection of polynomials could depend on minimum error of objective function and complexity of polynomial type. In this study, quadratic polynomial was utilized for modeling of scour depth around different types of bridge piers. The weighting coefficients in Equation (7) were calculated using regression techniques so that the difference between actual output y and the calculated one $\hat{y}$ for each pair of x_i; x_j as input variables was minimized. In this way, the weighting coefficients of quadratic function G_i were obtained to optimally fit the output in the whole set of input–output data pairs, that is,

$$E = \frac{\sum_{i=1}^{M} (y_i - G_i())^2}{M} \rightarrow \min \quad (9)$$

RESULTS AND DISCUSSION

In this section of the study, DTF and GMDH were developed to evaluate the effect of sediment on aquatic ecosystems, and results were compared against linear regression models. In the first step, DTF was used to assess the relative importance of variables on SEV. Here is an outline of the algorithm used to construct a DTF: (1) take a random sample of N observations from the data set with replacement (this is called 'bagging'); (2) using the rows selected in step 1, construct a decision tree. Build the tree to the maximum size and do not prune it; (3) repeat steps 1 and 2 a large number of times, constructing a forest of trees; (4) to 'score' a row, run the row through each tree in the forest and record the predicted value (i.e., terminal node) that the row ends up in (just as you would score using a single-tree model). For a classification analysis, use the predicted categories for each tree as 'votes' for the best category and use the category with the most votes as the predicted category for the row.

Table 3 | Relative importance of variables on SEV

Exposure duration (h)	100
Concentration (mg/L)	62.5
Life stage	25.4
Group	10.7

As can be seen (Table 3), exposure duration is the most important factor on SEV. Statistical measures, such as the NMSE, the correlation between actual and predicted, RMSE, and mean absolute percentage error were employed for qualitative evaluation of the models (Table 4).

In the second step, the steps discussed in the section 'Group method of data handling' are used to design a GMDH model to predict the SEV. In this section, the GMDH network was improved using back propagation algorithm. This method included the two main steps. First, the weighting coefficients of quadratic polynomial were determined using least square method from input layer to output layer in the form of a forward path. Second, weighting coefficients were updated using back propagation algorithm in a backward path. Again, this mechanism could be continued until the error of training network (E) was minimized. Two sets of input data are used during the training process: (1) the primary training data and (2) the control data which are used to stop the building process when over-fitting occurs. The control data typically have about 20% as many rows as the training data. Two hidden

Table 4 | Results of error statistics calculated SEV

Correlation between actual and predicted	0.8290
RMSE (root mean squared error)	1.7626
MAPE (mean absolute percentage error)	19.6784
NMSE (normalized mean square error)	0.31823

layers were considered for each model. To genetically design such networks, a population of 10 individuals with a cross-over probability of 0.7, mutation probability of 0.07, and 600 generations was used; it appeared that no further improvement could be achieved for such a population size. Equations (10)–(14) and Figures 2–6 show the results from this method to predict the SEV. We also performed *t*-tests and *p*-tests to test whether the difference between

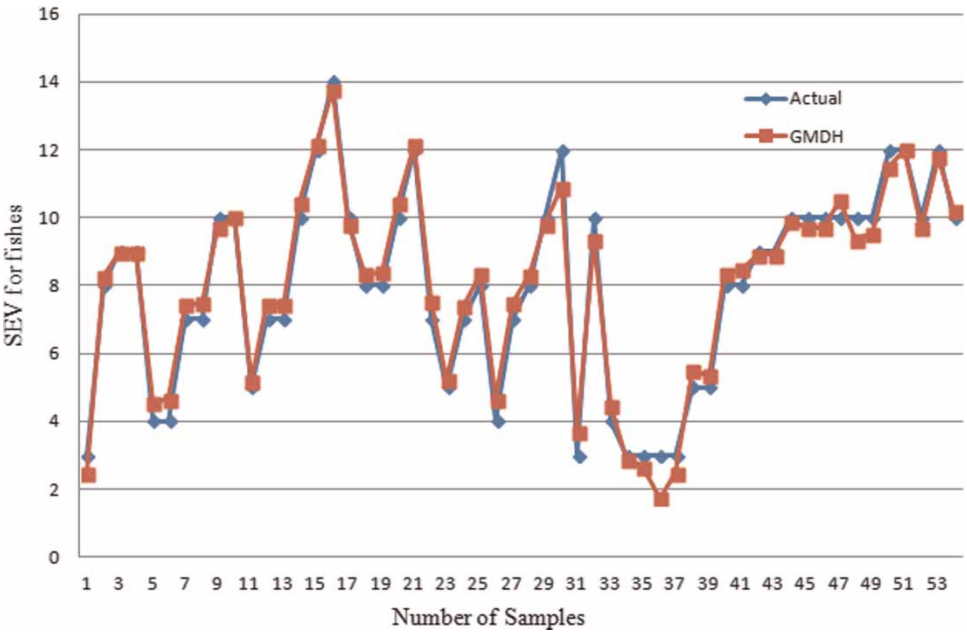

Figure 2 | Results of GMDH for adult salmonids and rainbow smelt.

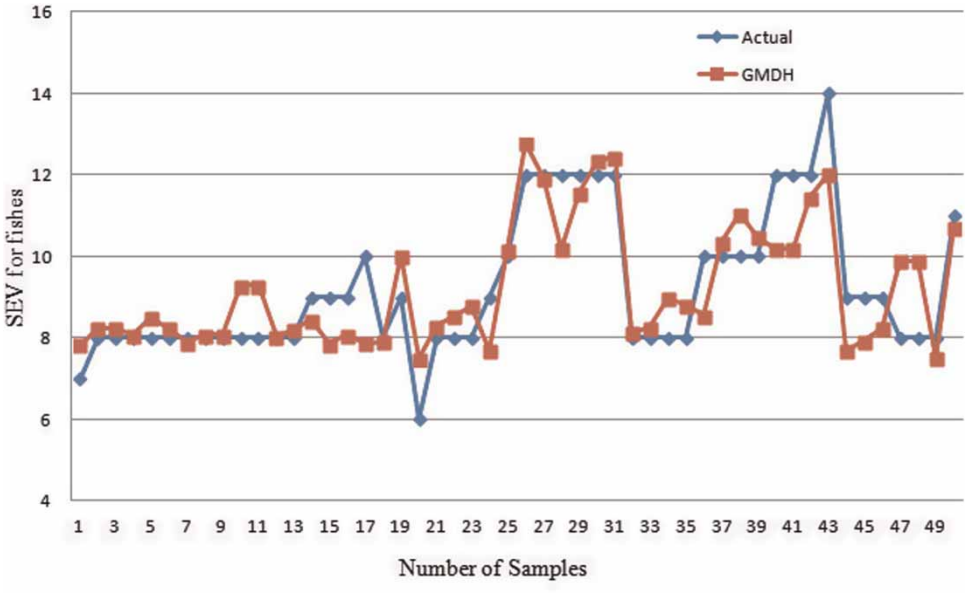

Figure 3 | Results of GMDH for juvenile salmonids.

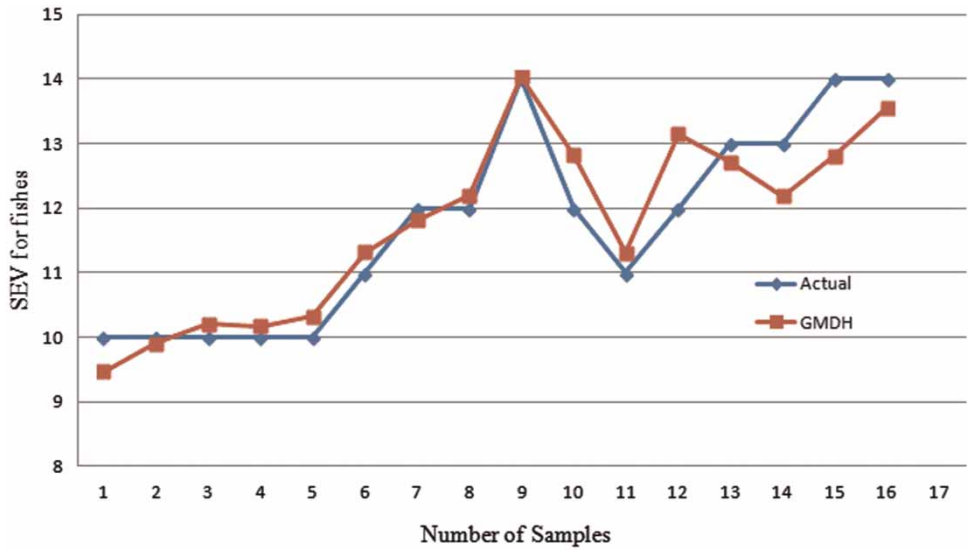

Figure 4 | Results of GMDH for salmonid eggs and larvae.

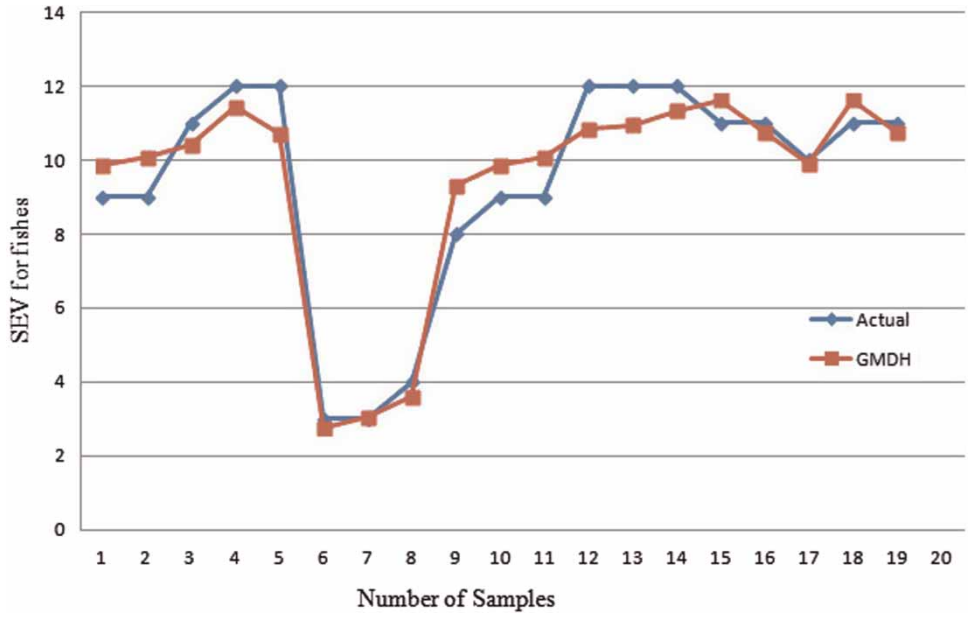

Figure 5 | Results of GMDH for non-salmonid eggs and larvae.

actual data and results obtained by GMDH are statistically significant or not (Table 5).

$$\begin{aligned}&\text{SEV (for adult salmonids and rainbow smelt)}\\&\quad=\text{Log concentration (mg/L)}\times-0.8697\\&\quad+\text{Log concentration (mg/L)}\\&\quad\times\text{Log exposure duration (h)}\times\ 0.4377\\&\quad+\text{Log exposure duration (h)}\times 3.886\end{aligned}\tag{10}$$

$$\text{MAE}=0.3781\ \text{RMSE}=0.4465\ R2=0.9883$$

$$\begin{aligned}&\text{SEV (for juvenile salmonids)}\\&\quad=15.28+\text{Log concentration (mg/L)}\times-2.415\\&\quad+\text{Log concentration (mg/L)}\\&\quad\times\text{Log exposure duration (h)}\\&\quad\times 0.0543+\text{Log concentration}^2\text{(mg/L)}\times 0.2024\end{aligned}$$

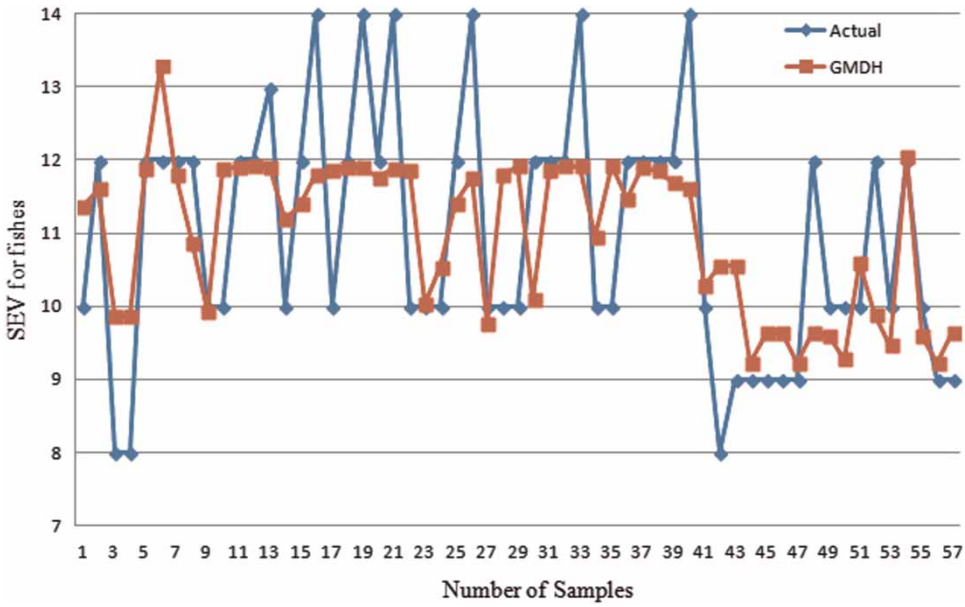

Figure 6 | Results of GMDH for adult non-salmonids.

Table 5 | The *t*-test and *p*-test values for each group

Group	*t*-test	*p*-test	df	The result at $p < 0.05$
Adult salmonids and rainbow smelt	0.1058	0.9158	106	Not significant
Juvenile salmonids	0.0701	0.9442	98	Not significant
Salmonid eggs and larvae	1.30×10^{-5}	0.9999	30	Not significant
Juvenile salmonids	5.00×10^{-6}	0.9999	36	Not significant
Adult non-salinonids	9.00×10^{-6}	0.9999	112	Not significant

$$+ \text{Log exposure duration (h)} \times -0.6366 + \text{Log exposure duration}^2(h) \times 0.0442 \quad (11)$$

$$\text{MAE} = 0.7787 \ \text{RMSE} = 0.9875 \ R2 = 0.8214$$

$$\text{SEV (for salmonid eggs and larvae)} = 4.665 + \text{Log concentration (mg/L)} \times 0.7655 + \text{Log exposure duration } (h) \times 0.7376 \quad (12)$$

$$\text{MAE} = 0.4412 \ \text{RMSE} = 0.5634 \ R2 = 0.9246$$

$$\text{SEV (for juvenile salmonids)} = -12.81 + \text{Log concentration (mg/L)} \times 9.677 + \text{Log concentration (mg/L)} \times \text{Log exposure duration } (h) \times 0.4975 + \text{Log concentration}^2 \text{ (mg/L)} \times -1.006 + \text{Log exposure duration } (h) \times -2.402 \quad (13)$$

$$\text{MAE} = 0.6866 \ \text{RMSE} = 0.7934 \ R2 = 0.9620$$

$$\text{SEV (for adult nonsalinonids)} = 15.94 + \text{Log concentration}^{-1} \text{ (mg/L)} \times -108.1 + \text{Log concentration (mg/L)} \times \text{Log exposure duration } (h) \times -0.0694 + \text{Log concentration}^{-1}\text{(mg/L)} \times \text{Log exposure duration } (h) \times 8.871 + \text{Log concentration}^{-1}\text{(mg/L)} \times \text{Log exposure duration}^{-1} (h) \times 195.7 \quad (14)$$

$$\text{MAE} = 0.9787 \ \text{RMSE} = 1.273 \ R2 = 0.6398$$

Finally, when the analysis of the prediction model for SEV was completed, the performance results were compared with those obtained using traditional equations. Correlation coefficient (R^2) is the commonly used prediction error indicators in the testing stage. The regression

equations and correlation between actual and predicted values are (Newcombe 1997)

$$\mathrm{SEV} = 1.0642 + 0.6068(\ln(x)) + 0.7384(\ln(y)),\ R^2 = 0.6009;\ \text{for juvenile and adult salmonids} \quad (15)$$

$$\mathrm{SEV} = 1.6814 + 0.4769(\ln(x)) + 0.7565(\ln(y)),\ R^2 = 0.6173;\ \text{for adult salmonids} \quad (16)$$

$$\mathrm{SEV} = 0.7262 + 0.7034(\ln(x)) + 0.7144(\ln(y)),\ R^2 = 0.5984;\ \text{for juvenile salmonids} \quad (17)$$

$$\mathrm{SEV} = 3.7466 + 1.0946(\ln(x)) + 0.3117(\ln(y)),\ R^2 = 0.5516;\ \text{for eggs and larvae} \quad (18)$$

$$\mathrm{SEV} = 4.0815 + 0.7126(\ln(x)) + 0.2829(\ln(y)),\ R^2 = 0.6998;\ \text{for adult freshwater nosalmonids} \quad (19)$$

where x is mg/L and y is hours. Correlation between actual and predicted was employed for qualitative evaluation of the models. It can be seen that when the results generated by GMDH were compared with traditional regression models, the GMDH was more accurate with higher recognition rate with minimal errors and forecast accuracy and strong practical value in predicting the SEV (correlation between actual and predicted for GMDH method = 0.8673 and correlation between actual and predicted for traditional regression (from Equations (15)–(19) = 0.6160 on average).

SUMMARY AND CONCLUSIONS

In this study, DTF and GMDH were used successfully for prediction of SEV based on concentration of SS and duration of exposure on fishes. Decision tree forest employed for evaluation the relative importance of variables on SEV. The results show that exposure duration is the most important parameter on SEV. Group method of data handling network was designed by trial-and-error method featuring back propagation algorithm, and minimum error of each network was met. Group method of data handling proposed five equations for evaluation of SVE. Results showed that combinations of iterative and evolutionary algorithms with the GMDH network provided better prediction of SEV than traditional equations.

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