Vol. 37: 145-152, 1999 | DISEASES OF AQUATIC ORGANISMS
Dis Aquat Org | Published July 30

A Monte Carlo simulation model for assessing the risk of introduction of *Gyrodactylus salaris* to the Tana river, Norway

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ABSTRACT: The Tana river in northern Norway, the most productive salmon river in Europe, is free of *Gyrodactylus salaris*. Currently there is one salmon farm in operation on the Tana fjord. Because of the strong association between stocking of rivers with salmon and infestations with *G. salaris* there is national and international concern that the existing farm might lead to the introduction of the parasite to the Tana river. In response to these concerns a quantitative analysis of the risk of introduction of *G. salaris* to the Tana river was undertaken. A scenario tree, the Monte Carlo simulation model and results of the simulations including sensitivity analyses are presented and discussed. Results show that the probability of introduction of *G. salaris* to the Tana river via transfer of smolt to the existing salmon farm is extremely low primarily due to the low probability that the transferred smolt become infested. The total risk was very sensitive to changes in the salinity of the water at the sea site.

KEY WORDS: *Gyrodactylus salaris* · Atlantic salmon · Norway · Risk assessment · Monte Carlo simulation model

INTRODUCTION

Gyrodactylus salaris (Monogenea), an ecto-parasite of salmonids, causes significant losses in both wild and farmed Atlantic salmon presmolt stocks. The parasite was first reported in Norway in 1975 and to date it has been found there in 40 salmon rivers and 38 farms (Direktoratet for Naturforvaltning 1995). Eleven of the farms raise salmon and 27 raise rainbow trout. An association between stocking rivers with smolt from infected hatcheries and the geographical distribution of the parasite has been demonstrated (Johnson & Jensen 1986). Because of the serious economic and environmental impacts of the parasite, several procedures and regulations have been instituted in efforts to prevent the further spread of the parasite and to eradicate it from infected rivers and farms. To eradicate *G. salaris*, rivers are treated with rotenone which kills the fish and consequently the parasite (Directoratet for Naturforvaltning 1995, Johnsen et al. 1989, Johnsen & Jensen 1991) As a result of rotenone treatments, 23 of 40 infested rivers and all farms are now free of *G. salaris* (Directoratet for Naturforvaltning 1995, Mo unpubl.).

The consequences of *Gyrodactylus salaris* infestations are severe. Two years after introduction of *G. salaris* the number of young salmon in infested rivers decreased by about 50%, and after 5 to 6 yr only 2 to 5% survived past the second or third winter (Johnsen & Jensen 1992). Estimated yearly total losses of 250 to 350 tons of salmon for both sea and river fishing catches have been reported (Johnsen & Jensen 1985, Dolmen 1987). Additional losses due to damage to sport fishing and the costs of surveillance, control and eradication of the parasite must also be considered.

The Tana river, in northern Norway, the most productive river in Europe in terms of tonnage of wild and farmed salmon harvested (Fylksmannen i Finnmark unpubl., cited in Fylkesveterinæren for Troms og Finnmark 1996), is free of *Gyrodactylus salaris*. At present, there is one salmon farm in operation on the Tana fjord but an additional farm has been contemplated. There

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have been national and international fears that the existing farm or a future farm might lead to the introduction of the parasite to the Tana river. In response to these fears, a quantitative assessment of the probability of introduction of *G. salaris* to the native Tana river salmon via the introduction of smolt to the commercial farm in the Tana Fjord was undertaken.

METHODS

A scenario tree depicting the events that would have to occur in order for *Gyrodactylus salaris* to be introduced to the Tana river was constructed (Fig. 1). The initiating event in the scenario is the occurrence of a new infestation of a salmon hatchery by *G. salaris*. Eggs from a single source are introduced into the smolt plant, where they are hatched and develop to smolt. The smolt are transferred to the sea site in tanks by trucks. The smolt are released into pens at the sea site and grow until harvested. Infestation of the fjord could occur by escape of infested fish or the detachment of living *G. salaris* and re-attachment to a feral fish. The final event in the scenario is the infestation of the Tana river. Each of the steps in the scenario was assigned a probability distribution function or probability of occurrence from which the total risk per transfer of smolt was estimated.

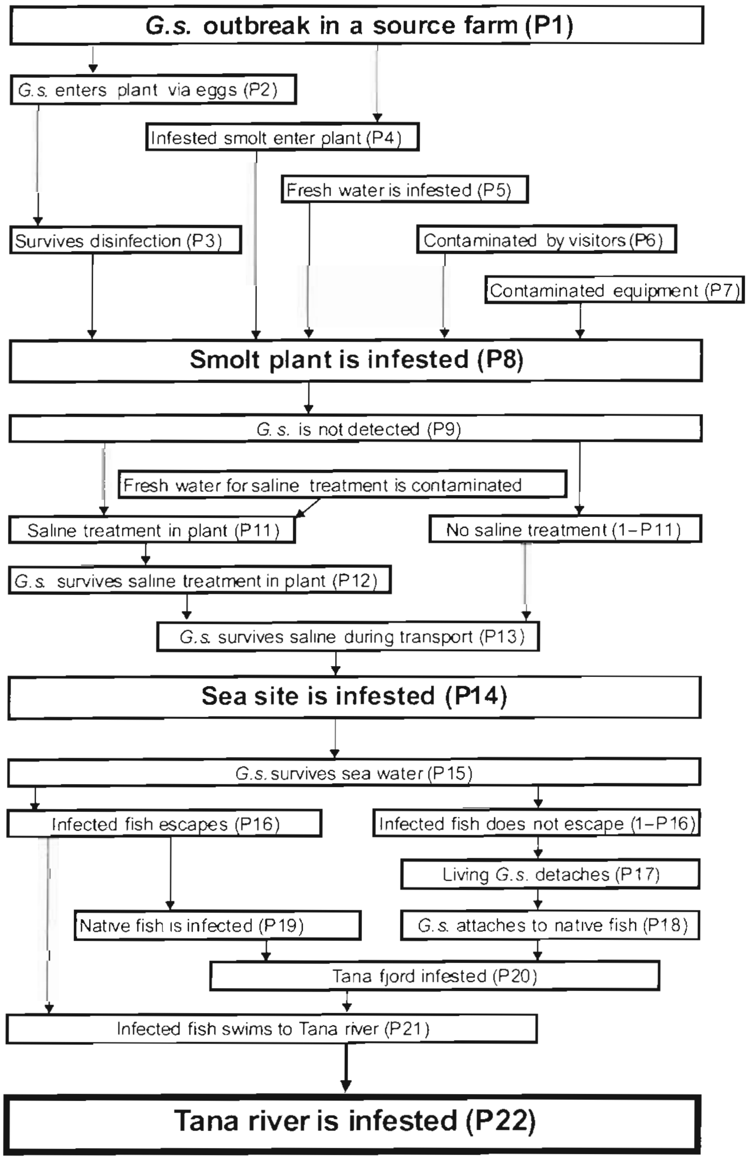

Fig. 1. Scenario tree for the introduction of *Gyrodactylus salaris* (G. s.) to the Tana river

The model was developed with the Excel spreadsheet (Microsoft Corporation, Seattle, WA, USA) with @Risk, a risk analysis software add-on (Palisade Corporation, Newfield, NY, USA). The sampling method was Latin hypercube and the Standard Recalc was Monte Carlo. Each simulation was run for 10000 iterations. Sensitivity of the output values to variations in the input values was assessed by calculating the rank order correlation coefficients with @Risk. The results are presented as a tornado chart (Vose 1996). Figs. 2 & 3 show the spreadsheet model with the formulae and values used for the calculations.

The following variables and probabilities were used to construct the simulation model (Vose 1996, Winston 1996). The notations for probability distribution functions provided by @Risk are written beginning with the letters 'Risk', e.g. RiskPoisson which indicates that a Poisson distribution will be sampled to generate the values in this cell.

Probability of a *Gyrodactylus salaris* infestation in a source farm that produces salmon eggs or smolt (P1). A Poisson distribution can be used to estimate the distribution of the number of events per unit of time based on the mean number of observed events per unit of time (Vose 1996). A source farm was defined as any potential source of eggs or smolt. The number of a source farms that are newly infested (Sfi) per year was estimated as RiskPoisson (11/23) because there had been 11 infestations of farms that produced eggs and smolt for other farms or smolt plants in the 23 yr since *G. salaris* was first reported in Norway (Mo unpubl.) This function generated a distribution of the number of new infestations that would be expected each year. The minimum, mean and maximum values of the distri-

	A	B
1	**RISK MODEL For *G. salaris* in theTana River, Norway**	
2		
3	*Probability of a GS infestation in a salmon egg or smolt source farm (P1)*	
4	*Number of new infestations per year (Sfi)*	=RiskPoisson(11/23)
5	*Number of smolt farms (Nf)*	418
6	*True prevalence of GS infested farms (Tp)*	=RiskBeta(B4+1,B5-B4+1)
7	*Probability that infested eggs enter the smolt plant (P2)*	=RiskBinomial(1,B6)
8	*Effectivity of disinfection*	0.9
9	*Percentage of viable GS after 1 disinfection*	=1-B8
10	*Number of disinfections*	3
11	*Probability of viable GS after 3 disinfections*	=B9^3
12	*Probability that GS survives disinfection in the smolt plant (P3)*	=B7*B11
13	*Probability that GS infested smolt enter the smolt plant (P4)*	0.000001
14	*Probability that GS infested fresh water enters the smolt plant (P5)*	=B6/(1*10^4)
15	*Probability of introduction of GS by visitors (P6)*	0.000001
16	*Probability of infestation by contaminated equipment (P7)*	0.000001
17		
18	*Probability that the smolt plant becomes infested (P8)*	=B12+B13+B15+B16+B14
19		
20		
21	*Total fish in the smolt plant (Fn)*	1000000
22	*Prevalence of GS in the smolt plant (Pi)*	=RiskIndepC("first")+RiskUniform(0,1)
23	*Number of fish tested (Nf)*	15
24	*Test sensitivity (Se)*	=RiskDepC("first",0.8)+RiskPert(0.05,0.4,0.8)
25	*Probability that GS is not detected at each test:*	=(1-(B23*B24)/B21)^(B22*B21)
26	*Total number of tests:*	=ROUND(RiskTriang(1,6,18),0)
27	*Probability of no detection of GS during routine health control (P9)*	=(B25)^(B26)
28	*Probability of Gs after inspections*	=B18*B27
29	*Probability that freshwater for saline treatment in plant is infested (P10)*	=B14
30		
31	*Saline treatment is done at smolt plant: 1=yes, 0=no (P11)*	=RiskSimtable({1,0})
32		
33	*Probability that GS survives saline treatment in the smolt plant (P12)*	=IF(B31=1,(0.00000001*B28),B28)
34	*Probability that GS infested freshwater is used in saline treatment (P10)*	=B29*1
35	*Probability of GS alive after saline*	=B33+B34
36	*Probability that GS survives transport in saline to the sea site (P13)*	=B35*0.75
37		
38	*Probability that the sea site is infested (P14)*	=B36
39		
40	*Probability for escape of fish within 240 hours (Pe)*	=RiskUniform(0,0.00235)
41		
42	*Probability that a fish with living GS escapes from the net (P15)*	=IF(B44>B43,1,0)
43	*Time of escape 0-240 hrs (Te)*	=RiskPert(0,24,240)
44	*Maximum survival time @ 1.4C 0.33-240 hours (Mts)*	=E84
45	*Probability that GS will be transmitted to wild fish in the river (Pi)*	1
46	*Probability that GS will be transmitted to wild fish via escape (P16)*	=B38*B40*B42*B45
47	*Probability that infected fish swims to Tana River (P21)*	=B38*B40*(B42*(RiskTriang(0,0.5,1)))
48		
49	*Probability of introduction of GS to the sea site (P13)*	=B38
50	*Maximum survival time @ 1.4C is 0.33-240 hours (Mts)*	=B44
51	*Time of detachment 0-240 hours (Td)*	=RiskUniform(0,240)
52	*Probability that live GS will be detached (P17)*	=IF(B50>B51,1,0)
53	*Probability that a detached GS will hit a free fish outside the net (Ph)*	0.001
54	*Probability that GS will attach to a free fish (Pa)*	0.5
55	*Probability that GS will be transmitted to wild fish in the river (P18)*	=B53*B54
56	*Probability that GS will attach to wild fish (P19)*	=(B49*B52*B55)
57	*Probability Tana Fjord is infested via detachment(P20)*	=B49*B56
58	*Total risk per transport of fish to the Tana River (P22)*	=B46+B47+B56
59		

Fig. 2. Upper part of the spreadsheet showing the construction and formulas

	A	B	C	D	E
71	Salinity	Survival time	Gradient	Intercept	Equation
72	10	240	=SLOPE(B72:B73,A72:A73)	=INTERCEPT(B72:B73,A72:A73)	=IF(A72<$L$71,IF($L$71<A73,$L$71*C72+D72,0),0)
73	15	78	=SLOPE(B73:B74,A73:A74)	=INTERCEPT(B73:B74,A73:A74)	=IF(A73<$L$71,IF($L$71<A74,$L$71*C73+D73,0),0)
74	20	42	=SLOPE(B74:B75,A74:A75)	=INTERCEPT(B74:B75,A74:A75)	=IF(A74<$L$71,IF($L$71<A75,$L$71*C74+D74,0),0)
75	30	=A74*B76/A76*B74	=SLOPE(B75:B76,A75:A76)	=INTERCEPT(B75:B76,A75:A76)	=IF(A75<$L$71,IF($L$71<A76,$L$71*C75+D75,0),0)
76	33	0.33			
77					
78					
79	Salinity	X	F(X)		Salinity
80	10	0	0		=RiskCumul(9,37,$A$80:$A$105,$C$80:$C$105)
81	11	1	0.0263157894736842		
82	12	0	0.0263157894736842		
83	13	0	0.0263157894736842		Survival time
84	14	0	0.0263157894736842		=SUM(E72:E75)
85	15	1	0.0526315789473684		
86	16	1	0.0789473684210526		
87	17	3	0.157894736842105		
88	18	2	0.210526315789474		
89	19	1	0.236842105263158		
90	20	3	0.315789473684211		
91	21	0	0.315789473684211		
92	22	1	0.342105263157895		
93	23	1	0.368421052631579		
94	24	0	0.368421052631579		
95	25	5	0.5		
96	26	1	0.526315789473684		
97	27	1	0.552631578947368		
98	28	0	0.552631578947368		
99	29	1	0.578947368421053		
100	30	6	0.736842105263158		
101	31	3	0.815789473684211		
102	32	5	0.947368421052632		
103	33	1	0.973684210526316		
104	34	0	0.973684210526316		
105	35	1	1		
106					

Fig. 3. Lower part of the spreadsheet showing the construction and formulas

bution were, 0, 0.47 and 5, respectively. The number of farms that produce eggs and smolt in Norway is 418. The distribution of the probability (p) of occurrence of an event based on the number of occurrences that were observed in a known number of opportunities can be estimated with a beta distribution (Vose 1996). True prevalence (Tp) is the probability that a farm is infested. Tp of infestation in source farms was modeled as RiskBeta (Sfi + 1, 418 + 1). This generated a distribution of Tp with a minimum of 5.66E-07, a mean of 3.51E-03 and a maximum of 2.71E-02.

Probability that *Gyrodactylus salaris* enters the smolt plant via eggs (P2). The probability that the source of eggs for this specific smolt plant was infested was estimated by RiskBinomial(1, Tp). This distribution will generate a 0 if the eggs are not from an infested source farm and a 1 if the source farm is infested. The percentage of times that a 1 is generated is the probability that eggs from an infested farm (and perhaps *G. salaris*) enter the smolt plant.

Probability that *Gyrodactylus salaris* survives disinfectant treatment in the smolt plant (P3). The maximum survival time for a free-living *G. salaris* is approximately 1 wk (Fylkesveterinæren for Troms og Finmark 1996). Based on experimental studies on the effects of iodine solutions on *G. salaris* (Mo unpubl.), it was estimated that each treatment with the iodine solution would be at least 90% effective in killing *G. salaris*. It was assumed that each batch of eggs would be treated 3 times. Therefore, the risk of survival after disinfection was estimated by $P2 \cdot (1 - 0.9)^3$.

Probability that *Gyrodactylus salaris* infested smolt enter the smolt plant (P4). The probability of infested smolt entering this smolt plant was estimated to be 0.0% because of the regulation prohibiting the entry of live smolt. Only eggs are allowed to be introduced into this smolt plant. However, a value of 1E-08 was used in the model because 0 risk is unattainable and it is lower than 1E-06, which is considered 'negligible risk or no significant risk' in human health and environmental risk studies (Ahl et al. 1993).

Probability that *Gyrodactylus salaris* infested fresh water enters the smolt plant (P5). This was estimated as $P2/10^4$. If there were a source of infestation in the fresh water the probability could not be greater than the risk that the source of the eggs was infested. Because there are no susceptible hosts in the fresh water supplying the smolt plant the risk was arbitrarily reduced by a factor of 1.0E-04.

Probability that visitors contaminate the smolt plant with *Gyrodactylus salaris* (P6). This was estimated to be zero (0.0%) because contamination by visitors would almost have to be a deliberate act and access to the plant by visitors is severely restricted. The actual value used in the model was 1E-08.

Probability of infection by contaminated equipment (P7). This probability was estimated as 0.0% because there is no sharing of equipment between plants or between areas within the plant. The actual value in the model was 1E-08.

Probability that the smolt plant is infested (P8). The overall probability of infestation of the smolt plant was calculated according to the formula: $P8 = (P1 \cdot P2 \cdot P3) + P4 + P5 + P6 + P7$.

Probability that *Gyrodactylus salaris* is not detected during routine health inspection in the smolt plant (P9). A routine health inspection in the smolt plant consists of gross visualization and microscopic examinations of scrapings from 15 fish. The fish undergo inspections 1 to 18 times during the hatching/growing phase. The sensitivity of the procedures in detecting *G. salaris* is dependent on the prevalence of infested fish, the number of parasites on each fish and the number of times the fish are tested. The sensitivity of the routine examinations was estimated to be near 0% very early but near 100% at later stages when all fish are affected by many parasites. The prevalence of infected fish (Pi) was estimated by RiskUniform(0, 1). This function generated a probability distribution with a minimum of 6.74E-05, a mean of 0.5 and a maximum of 99.99%. The sensitivity of the test procedures (Se) was estimated as a minimum of 5%, most likely 40% and a maximum of 80%. This was modeled by RiskPert(0.05, 0.40, 0.80) (Vose 1996). Since the sensitivity of the examination procedure is dependent on the prevalence of infested fish, sensitivity was correlated with the prevalence with a coefficient of 0.8 (Vose 1996). Therefore, P9 was calculated as $1 - (Pi \cdot Se)$.

Probability that fresh water used for saline treatment is infested (P10). The 2.0% saline solution used to treat the smolt is made by mixing salt with fresh water. The source of the water is the same as for the rest of the plant. Therefore, the probability (P10) is the same as P5.

Saline treatment is or is not done in the plant (P11). Two simulations of 10000 iterations each were done. If saline treatment was done a value of 1 was generated by the @Risk function, RiskSimtable({1, 0}). If no saline treatment was done the value generated was 0. These 2 values were used in the calculation of P12.

Probability that *Gyrodactylus salaris* survived saline treatment in the smolt plant (P12). The probability that *G. salaris* survives the saline treatment in the plant prior to shipment, given that the saline treatment was done, was estimated as 1E-08 because the maximum survival time of *G. salaris* in 2.0% saline solution at 1.4°C is 4.6 h. Survival time shortens as water temperature increases (Soleng & Bakke 1997). The in-plant saline treatment is a minimum of 168 h at ambient temperature which is above 1.4°C. The value of P12 was set to 1E-08 if saline treatment was done as in Simulation #1 and 1 if no saline treatment was done as in Simulation #2.

Probability that *Gyrodactylus salaris* survives saline treatment during transport to the sea site (P13). The smolt are transported to the sea site by truck in tanks containing 2.0% saline solution. However, the transport time is less than 4 h so that the probability of survival was arbitrarily set at 75%, a conservative figure.

Probability that *Gyrodactylus salaris* infested smolt are released at the sea site (P14). The total probability that infested smolt are released at the sea site is: P14 = (P8•P9•P11•P12) + (P10•P12).

Probability of escape from the pen (Pe). The probability of escape from the pen was estimated by RiskUniform(0, 0.00235) based on the number of escapes occurring during the first 10 d after release in sea pens per number of releases (Fylkesveterinæren for Troms og Finnmark 1996). This generated a probability distribution with a minimum of 1.03E-07, mean of 1.17E-04 and a maximum of 2.35E-03. The probability of no escape was (1 – Pe).

Probability that a fish with living *Gyrodactylus salaris* escapes from the pen (P15). The distribution for the maximum time of survival (Mts) of *G. salaris* in the salinity at the sea site was estimated as follows: Salinity measurements were taken at the sea site over a 45 d period during which transfer of smolt takes place. These measurements were used to produce a cumulative probability distribution of the salinity, RiskCumul(9, 37, {x}, {p}) (Vose 1996).

The maximum survival times in 1.0, 1.5, 2.0 and 3.3% saline solutions at 1.4°C (Soleng & Bakke 1997) were used to develop linear functions describing the slope and intercept of each separate segment of the 'survival curve' such that for any salinity value generated an Mts at 1.4°C was calculated (Vose pers. comm.).

The time of escape (Te) was calculated as follows. Escapes can occur anytime after transfer. The time of transfer was set at 0 h. It was assumed that most escapes would occur during the first 24 h after transfer. Fish escaping more than 240 h after transfer to sea water would be unlikely to harbor living *Gyrodactylus salaris* (Soleng & Bakke 1997). Therefore, Te was calculated with the function RiskPert(0, 24, 240). This generated a distribution with a minimum of 1.75E-02, a mean of 55.99 and a maximum Te of 216.7 h.

If Mts was greater than Te the value generated for P15 was 1; otherwise the value was 0. The probability that a fish with living *Gyrodactylus salaris* escaped the pen (P15) was the percentage of times that a value of 1 was generated.

Probability that *Gyrodactylus salaris* is transmitted to a wild fish in the river (Pi). If a fish with living *G. salaris* escaped from the pen the probability that the Tana fjord and, ultimately, the Tana river is infested (Pi) was set at 100%.

Probability that *Gyrodactylus salaris* is transmitted to wild fish via escape (P16). This was calculated as: P14•Pe•P15•Pi.

Probability that a living *Gyrodactylus salaris* detached from an infested salmon (P17). The probability that a *G. salaris* would detach was set to 100%. If the parasite was dead by the time of escape this value was 0%. The Mts was calculated as explained in P15. The time of detachment (Td) was calculated with RiskUniform(0, 240) where detachment could occur with equal probability any time between the time of release (0) and 240 h, the maximum period of risk. If Mts was greater than Td a value of 1 was generated. If Mts was greater than Te the value generated for P17 was 1; otherwise the value was 0. Thus, the probability that a fish with living *G. salaris* escaped the pen (P15) was the percentage of times that a value of 1 was generated. The probability that *G. salaris* would detach and sink through the pen to the sea bottom during the first 240 h was estimated as 100%.

Probability that a living *Gyrodactylus salaris* attaches to a native salmon (P18). The probability that a detached *G. salaris* encounters a native salmon swimming under the pen (Ph) was estimated as 1.0E-03 based on the estimated relative numbers of fish inside and under the pen. The probability of attachment (Pa) was estimated as 0.5. Thus, P18 equaled P17•Ph•Pa.

Probability that *Gyrodactylus salaris* will infest a native salmon (P19). The probability that an escaped salmon with living *G. salaris* attached would encounter and infect a native salmon was calculated as 1.0E-02. This value was set higher than the probability that a detached *G. salaris* would encounter and attach to a native salmon because of the ability of the infected fish to travel away from the pen.

Probability that the Tana fjord would be infested with *Gyrodactylus salaris* via detachment (P20). The total probability (risk) of infestation of the Tana river by *G. salaris* via detachment was calculated as P13•P19.

Probability that an infected salmon would swim directly to the Tana river (P21). The probability distribution function RiskUniform(0, 1) was used to model the probability that an escaped, infested salmon migrates to the Tana river. This function was chosen because there was no information regarding this probability. This generated a distribution with a minimum probability value of 4.12E-03, a mean of 0.5 and a maximum of 0.993.

Table 1. Risk of introduction of *Gyrodactylus salaris* to the Tana river per transfer of smolt

	Minimum	Mean	Maximum	95th percentile
Probability of plant infestation				
Simulations #1 and #2	3.06E-06	6.85E-06	1.00E-03	4.02E-06
Probability of sea site infestation				
Simulation #1	5.97E-12	2.63E-07	2.70E-06	7.52E-07
Simulation #2	5.97E-12	4.97E-07	6.63E-04	1.28E-06
Total risk per transfer				
Simulation #1	0	1.60E-10	5.14E-09	9.02E-10
Simulation #2	0	2.33E-10	1.74E-08	1.26E-09

Probability that Tana fjord is infested with *Gyrodactylus salaris* by a single transfer of smolt (P22). This was calculated as P19 + P20 + P21.

RESULTS

The results are presented in Table 1. Simulation #1 is with saline treatment of the smolt prior to transfer and Simulation #2 is without saline treatment. The results are also shown as cumulative probability distributions in Fig. 4. The results show that the risk of infestation of the Tana river by *Gyrodactylus salaris* via introduction of salmon smolt to this specific sea site is extremely low. In Simulation #2, when saline treatment was not done, the maximum risk calculated in any of the 10000 iterations was 1.74E-08. In 65% of the iterations in both simulations the risk was estimated as 0%. In 95% of the iterations the risk was less than or equal to 9.02E-10 and 1.26E-09 in Simulations #1 and # 2, respectively. In addition, approximately 78% of the values were less than or equal to the mean value of both simulations.

Sensitivity analysis was done by calculating the rank-order correlation coefficients. Sensitivity analysis for Simulation #1 revealed that the salinity at the sea site was the factor with the highest correlation (-0.595) with the risk of introduction of *Gyrodactylus salaris* (Fig. 5). That is, the higher the salinity the lower the risk. Other factors, listed in descending order of correlation, included: time of escape, time of detachment, prevalence of *G. salaris* infected farms, probability of escape, the number of new infestations per year, the probability an infected fish swam to the Tana river, whether infected eggs entered the plant, the prevalence of *G. salaris* in the plant, the total number of inspections and sensitivity of the inspections.

In Simulation #2, the results (not shown) were similar except that the sensitivity of the inspection procedure ranked higher than the probability of an infected fish swimming to the Tana river, whether *Gyrodactylus salaris* entered the plant with eggs and the total number of inspections. The prevalence of *G. salaris* in the smolt plant ranked higher than the test sensitivity. Whether or not saline treatment in the smolt plant was done ranked below all of the above variables in a combined simulation where saline treatment was done in 50% of the iterations.

DISCUSSION

Risk assessment is a procedure that is often used when a decision must be made under conditions of uncertainty. Uncertainty can be a result of lack of, or insufficient, knowledge and the variability due to chance. Risk assessment consists of determining what can go wrong, how likely it is to go wrong and the consequences should it occur. The general steps in conducting a risk assessment are to construct a scenario

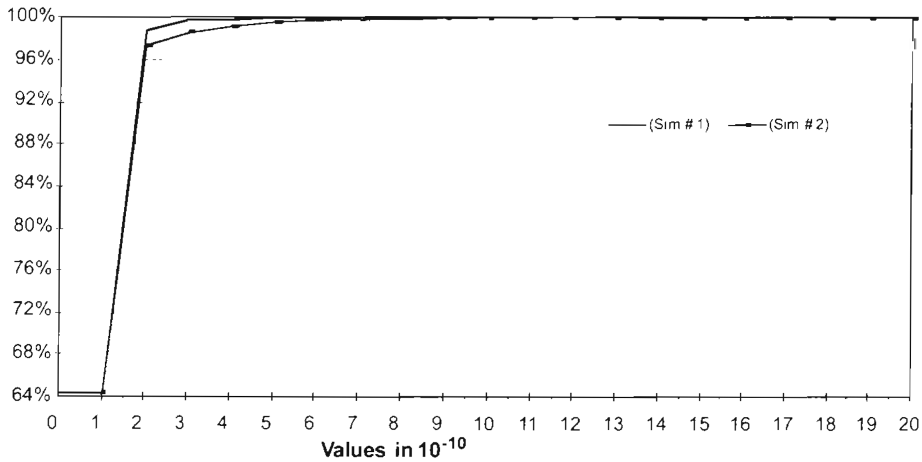

Fig. 4. Cumulative probability distributions for the risk of introduction of *Gyrodactylus salaris*. The distributions show that the effect of saline treatment in the smolt plant have minimal effect on the total risk per transport of fish. The primary effect of saline treatment is to narrow the range of the risk estimate. The chart also shows that approximately 65% of the time the calculated risk was 0%

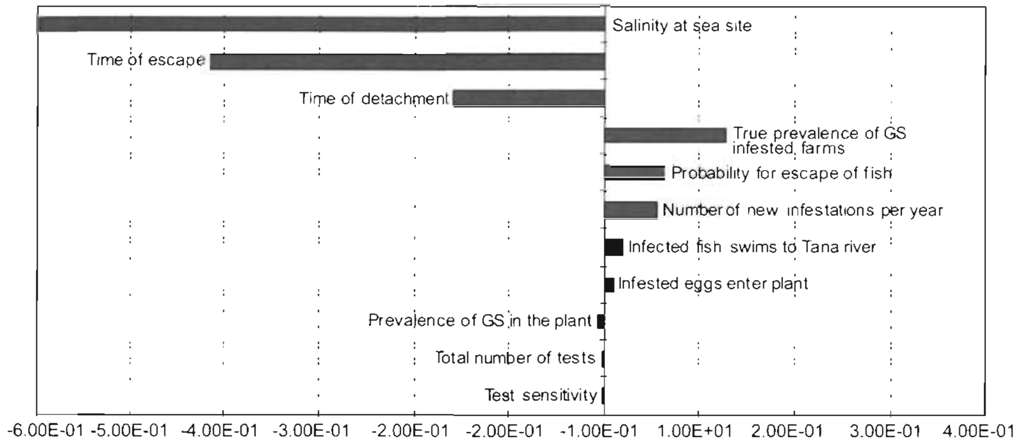

Fig. 5. Tornado graph depicting the rank order coefficients between the inputs and the risk of introduction of *Gyrodactylus salaris* in Simulation #1 (with saline treatment in the plant). The variables are shown in decreasing order of effect on the output

tree or flow diagram identifying the events or steps and pathways from the initiating event to the final outcome, to assign probabilities of occurrence to each event in the process and, finally, to calculate the total risk of occurrence. The assessment of the consequences, should an adverse event occur, should be the next logical step but that is beyond the scope of this project. To ensure that the results are accepted the model should be transparent. That is, every step and probability assigned are explained and justified.

Monte Carlo simulation models (Vose 1996, Winston 1996) are often used to assess risks because they utilize probability distribution functions in lieu of fixed probabilities, in multiple iterations, thus addressing the inherent uncertainties in natural systems. The results generated are probability distributions from which the minimum, maximum, mean and other more familiar parameters for risk can be calculated.

The results of the simulations demonstrate that the risk of introduction of *Gyrodactylus salaris* to the Tana river by transferring salmon smolt to the sea site is extremely small under the conditions imposed in the models. If any of the conditions should change or any of the assumptions are invalid the results would likely be much different. For example, the risk assessed in this analysis is that associated with smolt from a specific smolt plant where only eggs, and not smolt, are allowed to enter the plant. If the source of eggs were another plant or smolt were allowed to enter the plant the model assumptions would no longer be valid. It is for these reasons that all of the inputs and assumptions in a risk model must be transparent and justified by the best information available at the time. The input variables P4, P6, and P7 are included in the model only to demonstrate that these factors were considered in constructing the model. This allows flexibility so that if new information should surface the 'negligible risk' values of 1E-08 assigned to these variables could be changed to a value reflecting that particular risk.

The importance of treatment of the smolt in 2.0% saline solution prior to transfer to the sea site, one of the risk reduction measures that has been put into practice, was modeled where treatment was done in 50% of the iterations. All other variables in the model changed according to their respective probabilities or probability distributions. In the sensitivity analysis, saline treatment in the plant ranked number 7 of the rank-order correlation coefficients, suggesting that this procedure would not greatly reduce the overall risk.

This model incorporated measurements of the salinity of the sea water in the Tana fjord during the period when the smolt are normally released (Gjerp & Vaskinn 1989). The salinity data were combined with experimental data on the maximum survival time of *Gyrodactylus salaris* at various water temperatures and salinity levels (Soleng & Bakke 1997) to generate probability distributions of the survival times of *G. salaris* in relation to the time of escape from the pen or detachment and falling to the bottom. The salinity of the sea water had the highest rank-order correlation with the total risk in all simulations. These results show that ensuring high salinity at the sea site at the time of transfer is the procedure that would reduce the risk by the greatest amount.

The results of this analysis suggest that the risk of introduction of *Gyrodactylus salaris* to the Tana river via the transfer of smolt from this specific smolt plant is very small. However, these results should not be extrapolated to other plants or other situations where the estimated risk may be quite different. In addition to the value of the quantitated risk estimates generated, the modeling procedure is valuable in itself because it allows greater understanding of the entire system, and identifies information gaps and possible risk management options that can be simulated. The next logical step in the process is the evaluation of the economic, environmental and social consequences should introduction of *G. salaris* occur.

Risk models should be flexible and dynamic so that they can be revised if and when conditions change or better information becomes available. The results should not be interpreted as 'the answer' but as some of the information a risk manager can consider when arriving at a decision. Simulation modeling is an supplement to, not a substitute for, carefully conducted scientific investigations. It should also be emphasized that, in this case, the results are theoretical, probably impossible to validate and depend on humans following the rules. It should also be remembered that low probability events sometimes do occur.

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Editorial responsibility: Wolfgang Körting, Hannover, Germany

Submitted: November 10, 1998; Accepted: March 3, 1999
Proofs received from author(s): July 12, 1999