Assessing Ecological Risk of Chemicals in Lake Suwa: A Modeling Approach

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Abstract

The Comprehensive Aquatic System Model for Lake Suwa, CASM_SUWA, was developed and evaluated to examine its applicability for site-specific ecological risk assessment of chemicals. CASM_SUWA is a bioenergetic ecosystem effects model that simulates the daily production dynamics of populations, including predator-prey interactions, through time in relation to daily change of light intensity, water temperature, and nutrients availability. A reasonable deterministic model simulation that represents the characteristics of the Lake Suwa ecosystem was established by calibrating the model parameters. The risk estimation of linear alkylbenzene sulfonates, LAS, on the model species implies that the model could provide additional information to improve ecological risk assessment of chemicals in aquatic ecosystems.

1. Introduction

A number of single species toxicity tests have been developed and implemented to identify hazard of chemicals. The results from these tests provide useful information for determining the relative toxicity of different chemicals. However, applying these results to draw conclusions about chemical effects on natural systems composed of complex ecological interaction is questionable. In order to improve the assessment of chemical effects on natural systems, ecological modeling would be an useful technique. Ecological models, which can be defined as a simplified representation of an ecological system of interest, could be the only option for assessing chemical effects under circumstances where field experiments cannot be conducted. Several reviews of ecological models for use in ecological risk assessment have been published (Barnthouse *et al.*,1986, Emlen, 1989, Barnthouse, 1992).

In the study presented here, the Comprehensive Aquatic System Model (DeAngelis *et al.*, 1989, Bartell *et al.* 1992) for Lake Suwa, CASM_SUWA, was developed and evaluated. Although CASM has been evaluated using an arbitrarily defined assemblage of populations, rather than site-specific taxa, and a modified version of CASM, called LERAM, was evaluated using data from littoral enclosure studies (Hanratty and Stay, 1994), only a few attempts have been made to examine its applicability to actual ecological risk assessment. Thus, the purpose of this study is to examine the applicability of CASM_SUWA to site-specific ecological risk assessment of chemicals in natural aquatic ecosystems. The specific objectives in this study were to 1) develop CASM_SUWA to estimate the potential risk posed by chemicals in Lake Suwa, 2) determine the parameter data set suitable for modeling the populations in Lake Suwa, and 3) calculate the risk of biomass change posed by LAS.

2. CASM_SUWA

CASM_SUWA was developed by modifying the food web and environmental structures of the Comprehensive Aquatic System Model to represent characteristics of the Lake Suwa ecosystem. CASM is a bioenergetic ecosystem effects model that simulates the daily production dynamics of populations, including predator-prey interactions, through time in relation to daily change of light intensity, water temperature, and nutrients availability. CASM uses single species toxicity data to estimate the potential chemical effects on biomass production in aquatic ecosystems. The model species used in CASM_SUWA are listed in Table 1. The Lake Suwa adaptation of the CASM model consists of five phytoplankton populations, three zooplankton populations, two benthic insect populations, a single benthic invertebrate population, three omnivorous fish populations, and a single piscivorous fish population.

The food web structure of CASM_SUWA is shown in Figure 1. The arrows in this diagram represent the flow of energy and biomass. Each box or circle represents one model population or non-living component. The growth of each population is determined by the environmental conditions, the biomass of the populations, and the specific bioenergetic parameters of each population. Table 2 lists the parameters for the producer, the consumer, and environmental conditions used in CASM_SUWA.

Table 1. Population structure and toxicological data used in CASM_SUWA

Population	species	Assay	LAS concentration (mg/l)
Phytoplankton	1 *Cyclotella sp.*	96h-EC50	20
	2 *Melosira*	96h-EC50	20
	3 *Astrionella spp.*	96h-EC50	20
	4 *Microcystis*	96h-EC50	10
	5 *Micractinium pusillum*	96h-EC50	50
Zooplankton	1 *Bosmina longirostris*	48h-LC50	2.71
	2 *Filinia longiseta*	48h-LC50	2.71
	3 *Keratella quadrata*	48h-LC50	2.71
Benthic insect	1 *Chronomidae*	48h-LC50	3
	2 *Tubifex tubifex*	48h-LC50	1.8
Benthic invertebrate	1 *Macrobrachium longipes*	48h-LC50	3
Omnivorous Fish	1 *Hypomesus olidus*	48h-LC50	4.7
	2 *Carassius carassius*	96h-LC50	4.4
	3 *Cyprinus carpio*	96h-LC50	4.4
Piscivorous Fish	1 *Prasilurus asotus*	96h-LC50	4.4

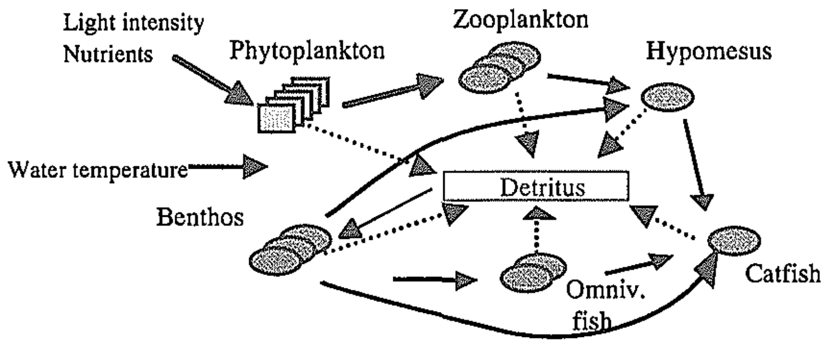


Figure 1. Depiction of CASM_SUWA food web.

Table 2. Parameters used in CASM_SUWA

Producers	*Consumers*	*Environmental*
Initial biomass B_0 [g-C/m^3]	Initial biomass B_0[g-C/m^3]	Daily water temperature T [°C]
Optimal temperature T_o [°C]	Optimal consumption temperature Toc [°C]	Daily light intensity I [E/m^2·d]
Maximum photosynthesis rate P_m [1/d]	Maximum consumption rate Cm [1/d]	Daily N, P, Si level [mg/l]
Light saturation intensity I_S [E/m^2·d]	Maximum respiration temperature Tr [°C]	
Sinking rate S [1/d]	Maximum respiration rate R [1/d]	
Michaelis-Menten constants	Excretion rate E [-]	
for K_P, K_N and K_{Si} [mg/l]	Mortality rate M [1/d]	
Mortality rate M [1/d]	Specific dynamic action D [-]	
Respiration rate R [1/d]	Prey preference coefficients *wi* [-]	
	Assimilation coefficients *ai* [-]	

The fundamental equations used in CASM_SUWA to simulate daily biomass change of each population are briefly described in Table 3. Detailed descriptions of the equations used in the model can be found in previous studies (Miyamoto *et al.*, 1998, DeAngeliset *et al.*, 1989).

Table 3. Equations used in CASM_SUWA

Primary Producers

$$\frac{dB}{dt} = B\{Pm \cdot f(N,P,Si) \cdot g(I) \cdot h(T) - R \cdot h(T) - S - M - G\}$$

where

$$f(N,P,Si) = \min\left[\frac{N}{KN + N}, \frac{P}{KP + P}, \frac{Si}{KSi + Si}\right],$$

$$g(I) = \frac{0.316[\exp\{(-I/Is)\exp(-0.2z - 0.1Z)\} - \exp(-I/Is)]}{0.2 + 0.1Z},$$

$$h(T) = \{(To + 10 - T)/10\}^{1.5} \exp[1.5 - \{1.5(To + 10 - T)/10\}],$$

z = Average depth of lake
Z= Sum of biomass values for all phytoplankton

Consumers

$$\frac{dB}{dt} = B\{C(1 - D - U) \cdot h(T) - R \cdot h(T) - M - G\},$$

where

$$C = Cm\sum_j\{a_j w_j B_j/(B + \sum_j w_j B_j)\},$$

$$G = \sum_k\{Cm_k h(T_k) w_k B_k/(B + \sum_k w_k B_k)\},$$

Bj : the biomass of prey for taeget population
Bk: the biomass of predator for target population

CASM_SUWA incorporates a toxic effects submodel which extrapolates from single species toxicity data to potential effects of chemicals on biomass production in aquatic ecosystem (O'Neill, 1982). Since the toxic effects simulation method has been described in detail in previous studies (Bartell, 1990, Hanratty and Stay, 1994), only a brief description of the method is provided here. The effect on each model population is calculated by estimating the change in the bioenergetic rates for the expected water concentration of the chemical. The change in bioenergetic rates is predicted using data from single species toxicity tests. Bioenergetic rates are changed by the following steps: 1) each model equation is removed from the ecosystem model and growth is simulated under no-limiting conditions (e.g. constant light, temperature, and nutrients for phytoplankton, and constant temperature and no food for consumers), 2) a dimensionless scaling constant, called an effects factor, is determined to adjust the bioenergetic parameters so that the population biomass decreases by the expected loss against exposure concentration of the chemical. The effects factor for each population is calculated by running iterative simulations of the growth of that population for the duration of the toxicity test. During each simulation, the bioenergetic parameters are multiplied or divided by the effects factor required to simulate the decrease in biomass measured in the toxicity test. Once the effects factor for each population is obtained, the linear relationship between the exposure concentration and the effects factor is used to estimate an e_i value for each exposure concentration of the chemical.

Using the effects factors and considering uncertainties associated with extrapolation from the laboratory to the field and incomplete toxicity data, CASM_SUWA estimates the potential risk of chemicals on annual production for each population biomass. The uncertainties are considered by assigning distributions for each effects factor. The means, the ranges, and the standard deviations of each effects factor are specified. Repeated simulations, altering the bioenergetic model parameters with all effects factors chosen independently from their respective distributions by the Monte Carlo method, are performed to estimate the potential risk of chemicals on the annual total production for each population biomass. The risks are represented in the form of probabilities of the specified magnitude of increase or decrease in biomass by comparing the annual production values under toxic stress with the annual productions determined from a deterministic simulation under no toxic stress.

3. Field and Ecological Data

Data from the field and literature must be collected and compiled for the determination of the model inputs for CASM_SUWA and for the comparison of the model results with field data. Environmental input parameters, such as daily water temperature, light intensity and nutrients levels, were taken from the monitoring data of water quality in Lake Suwa (The Suwa Hydro., 1997). The observation data for biomass of phytoplankton and zooplankton in Lake Suwa were taken from theses at Shinshuu University (Kitamura, 1993, Arakawa, 1994). The qualitative biomass estimates for benthos and fish were available from other modeling studies for the lake (Japan Fisheries., 1995). The bioenergetic parameters used were mainly based on previous modeling studies relevant to CASM (e.g., DeAngelis *et al.*, 1989), biological and ecological literature (e.g., Jorgensen, 1979), and expert opinion. These useful parameters were used directly or adjusted to calibrate the model.

LAS, a major anionic surfactant used in many laundry and cleaning products, was selected for the purpose of the demonstration of the model. Toxicity data used for each model population were based on laboratory test results published previously (Table 1). For purposes of example, environmental exposure concentrations of LAS are assumed to be constant. The risks were estimated for four exposure concentrations: 0.005, 0.01, 0.05, and 0.1 mg/l.

4. Results

The model parameters were calibrated to produce a realistic representation of biomass change for the selected model species in Lake Suwa. Calibration of the model parameters was repeated until a reasonable representation of the model simulation for the lake was obtained. An example of the model species that represents a reasonable fit to the observed data for Lake Suwa is shown in Figure 2. The simulation began in March.

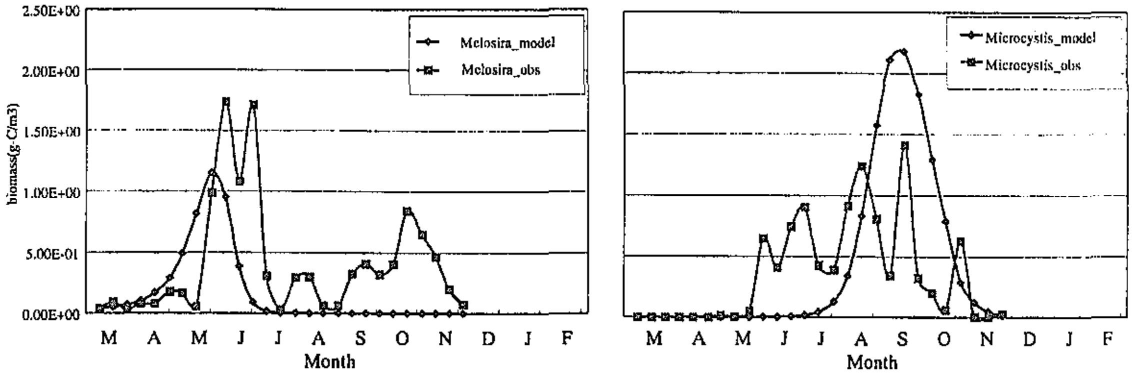


Figure 2. Comparison of the simulation results and the observed data for two phytoplankton species.

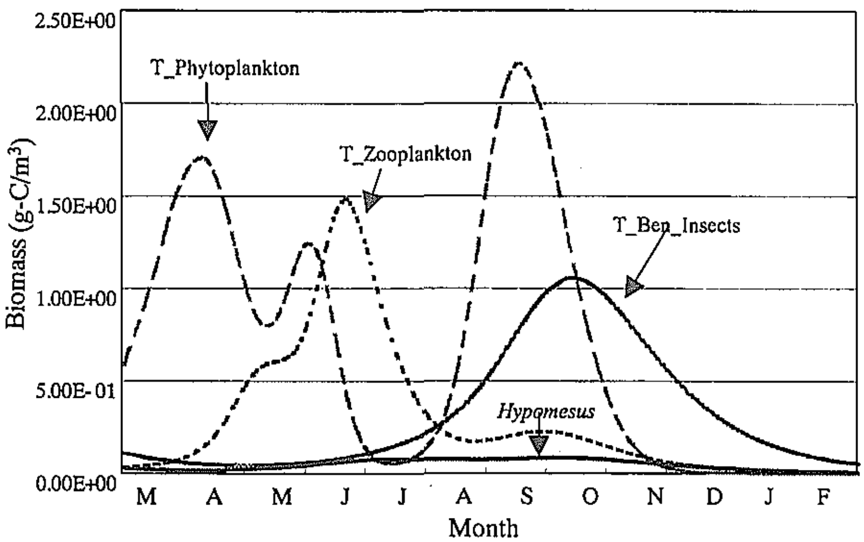


Figure 3. Seasonal changes of biomass for total phytoplankton, total zooplankton, total benthic insects, and *Hypomesus*

An established deterministic simulation of CASM_SUWA for each trophic level is shown in Figure 3. To simplify presentation, biomass for phytoplankton, zooplankton, and benthic insects were summed over the aggregated individual population. The change in biomass for phytoplankton shows peaks that correspond to the growth of diatoms in spring and the growth of blue-green algae in summer. With an increase of phytoplankton biomass, zooplankton biomass increases. Although the calibration of some trophic levels, such as benthos and fish, still must be improved against field data, CASM_SUWA provided a reasonable representation of the Lake Suwa ecosystem.

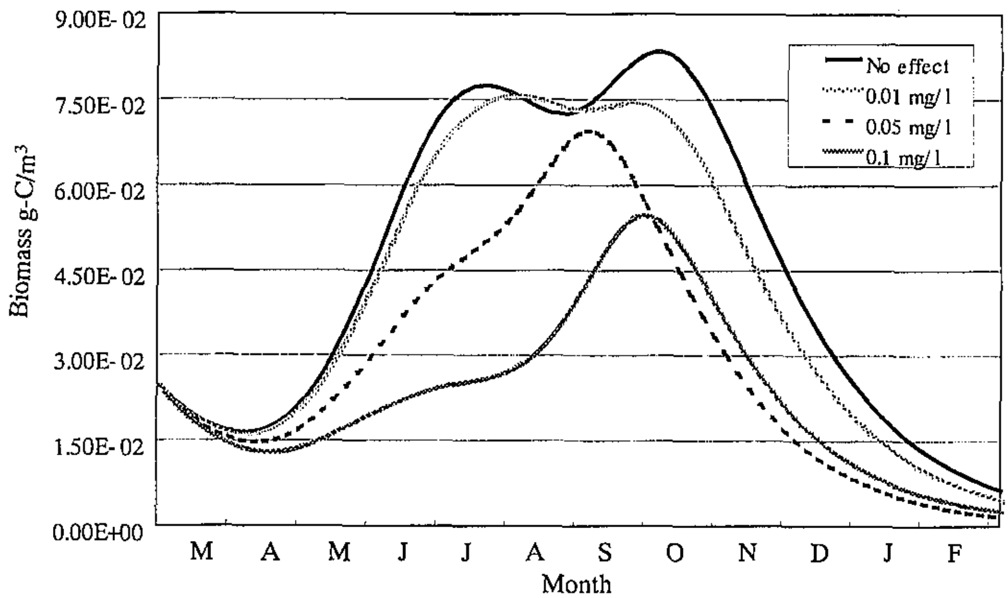


Figure 4. Biomass change for *Hypomesus* in relation to different LAS concentrations.

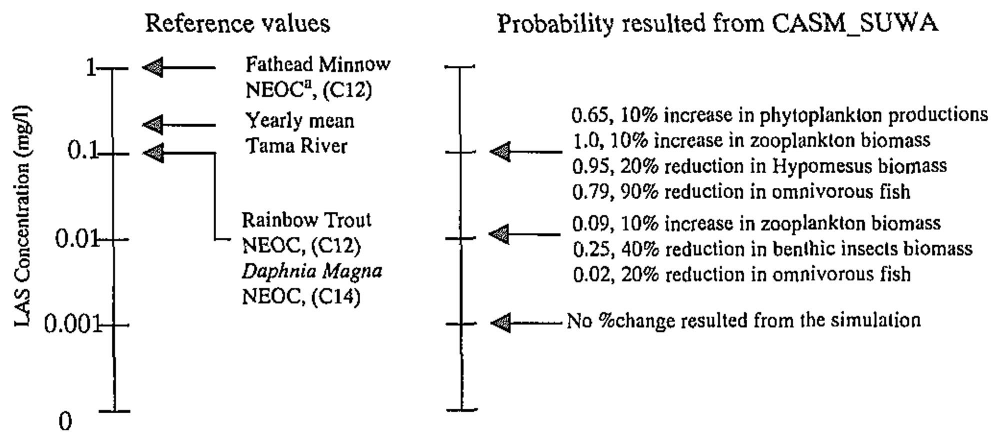
The risk posed by LAS on each population, based on 150 Monte Carlo iterations, was estimated in relation to different exposure concentrations. An example of biomass change for *Hypomesus* is illustrated in Figure 4. The visual comparison indicated that the *Hypomesus* biomass decreases with an increase in LAS exposure concentration.

The risk estimates for the model populations resulting from different LAS exposure concentrations are summarized in Table 4. The population of benthic insects was the most sensitive to LAS. In the assigned exposure concentration range, the probability of a 10% increase in annual production for phytoplankton and zooplankton increased with the increase in LAS exposure concentrations. This pattern of behavior suggested that the increase in the biomass of zooplanktons would be due to an increase in prey, phytoplankton, that are less sensitive to LAS, and a decrease in their predator, *Hypomesus*, which is relatively sensitive to LAS. The probability of biomass reduction was higher in omnivorous fish, which consists of *Carassius* and *Cyprinus* than in *Hypomesus*. This was due to not only their sensitivities to LAS, but also the decreased production of their prey. The LAS results demonstrated that CASM_SUWA estimated the risks of direct toxic effects on each population and the indirect ecological effects that propagate through the food web in the model ecosystem.

Table 4. Estimates of risk of %change in relation to LAS exposure

Exposure Concentration (mg/l)	species	% Change					
		+10	-10	-20	-50	-70	-90
0.005	Phytoplankton	0	0	0	0	0	0
	Zooplankton	0	0	0	0	0	0
	B. Insects	0	0.85	0.37	0	0	0
	Hypomesus	0	0	0	0	0	0
	O. fish[a]	0	0.06	0	0	0	0
0.01	Phytoplankton	0	0	0	0	0	0
	Zooplankton	0.04	0	0	0	0	0
	B. Insects	0	1	0.83	0.01	0	0
	Hypomesus	0	0	0	0	0	0
	O. fish	0	0.63	0.02	0	0	0
0.05	Phytoplankton	0.07	0	0	0	0	0
	Zooplankton	1	0	0	0	0	0
	B. Insects	0	1	1	1	0.81	0.31
	Hypomesus	0	0.97	0.63	0	0	0
	O. fish	0	1	1	0.44	0	0
0.1	Phytoplankton	0.65	0	0	0	0	0
	Zooplankton	1	0	0	0	0	0
	B. Insects	0	1	1	1	1	0.79
	Hypomesus	0	1	0.95	0	0	0
	O. fish	0	1	1	0.87	0.51	0

[a] In this risk estimate, O.fish corresponds omnivorous fish which consists of Carassius and Cyprinus.



[a] NEOC = no observed effect concentration.

Figure 5. Comparisons between some reference values and the simulation results in relation to LAS exposure.

The model results and some reference values for LAS exposure are shown in Figure 5. Yearly mean LAS concentration in the Tama River is shown in the figure as a reference environmental concentration (Takada, 1988). The NEOCs predicted from laboratory tests are considered to be a good indicator of the safe concentration of chemical for aquatic organisms in natural systems. However, the model results indicated that CASM_SUWA, which includes competitive and predator-prey interactions, imply a potential risk on populations in the model ecosystems at the same LAS exposure level of NEOC for rainbow trout and *Daphnia Magna* (Kimerle, 1989). Therefore, the model results imply that the modeling approach could provide additional information for establishing regulatory standards of chemicals.

5. Conclusions

The Comprehensive Aquatic System Model for Lake Suwa, CASM_SUWA, was developed and evaluated to examine the applicability to site-specific ecological risk assessment. In the model development phase, a deterministic model that is a reasonable representation of the Lake Suwa ecosystem was established. The results from risk estimates of LAS exposure on the model ecosystem demonstrated that the CASM_SUWA could provide additional information to improve the assessment of chemicals on aquatic ecosystems.

In order to improve the credibility and accuracy of the model, further evaluations are needed. It is important to identify its strengths and limitations by thoroughly examining the model using different chemicals and different sites before the model is applied for actual assessment of chemicals in real ecosystems.

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