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# 湖泊水库结构生态动态模型

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**摘要**: 综述了湖泊水库结构生态动态模型的研究进展及其在湖泊水库环境生态模拟中的应用。结果表明, 热力学理论为获取湖泊水库生态系统特性提供了一条整体性的途径, 热力学概念"㶲"可将生态学理论(达尔文理论)和热力学理论(最大㶲原理)很好地联系起来。引入㶲后, 许多重要模型参数的目标函数可根据最大㶲原理获得, 达尔文"适者生存"理论可被定量为一个生态约束条件用于开发湖泊水库结构生态动态模型, 从而使得提出的模型在生态上更合理, 在应用上更灵活, 为了更好地将㶲用于湖泊水库的生态模拟和环境管理中, 还需进一步对㶲的检验和优化进行讨论和研究。

**关键词**: 㶲; 生态模拟; 结构生态动态模型

## Structural ecodynamic model for lakes and reservoirs

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**Abstract**: This paper reviews the researches on the structural ecodynamic models for lakes and reservoirs and their applications in ecological modelling of lake and reservoir environment. The results follow that the thermodynamic theories provide a holistic approach for capturing the properties of lake and reservoir ecosystem, the thermodynamic concept "exergy" links well the ecological theory (Darwin's theory) with thermodynamic theory (the maximum exergy principle). By the application of exergy, a goal function of some important model parameters is obtained according to the maximum exergy principle, and Darwin's theory "survival of the fittest" can be quantified as an ecological constraint to develop the structural ecodynamic model for lakes and reservoirs, which makes the proposed model ecologically more reasonable and practically more flexible. However, in order to use effectively exergy in ecological modelling and environmental management of lakes and reservoirs, the camination and optimization of exergy are still needed to discuss and study further.

**Key words**: exergy; ecological modelling; structural ecodynamic model

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### 1 Introduction

With the development of computer technology, many models were developed to use in ecological modelling of lake and reservoir environment. the field covers a wide range of models, from population dynamics to oxygen balances in streams and lakes, and from eutrophication models to models of toxic substances in fresh water ecosystems. Jorgensen[1] divided the development of ecological modelling in limnology into five generations of models, the first generation were models of oxygen balance in a stream (the Street-Phelps model) and of the prey-predator relationship (the Lotka-Volterra model) developed in the early 1920s. The population dynamic models took place in the 1950s and 1960s and more complex river models developed in 1960s could be named the second generation of models. The third generation started around 1970 with the development of eutrophication models used in environmental management. The models from the late 1970s

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to the middle 1980s could be called the fourth generation of models. Since the middle 1980s modellers have proposed the fifth generation of models, which attempt to account for structural changes.

In this paper, the fifth generation of models——structural ecodynamic models for lakes and reservoirs are reviewed and their applications in environmental management and ecological research are analyzed. Based upon the reviews and analyses, it is pointed out that with the use of the thermodynamic concept exergy in ecological models, Darwin's theory of "survival of the fittest" can be quantified as an ecological constraint of ecological models to develop the structural ecodynamic models for lakes and reservoirs, and the changes in ecological structure and species composition of ecosystem can be reflected by the changing model parameters and the changing exergy values.

## 2 Structural ecodynamic model for lakes and reservoirs

The development of the structural dynamic models has recently been developed as a research direction within the traditional established discipline of ecological modelling[2,3]. The term structural dynamic refers to the ability of the models to perform changes in species composition and trophic structure of the ecosystem modeled. The development of this type of models was started in the area of aquatic ecosystem models, especially lake ecosystems, where the models through some years have reached a state to certain degree, they are able to give acceptable prognosis of the quantitative development of ecosystem as a consequence of changes in external factors influencing the system.

### 2.1 Exergy in ecosystems

The concept of exergy, through its definition by Evans[4] based on thermodynamic in formation, defined as deviation in entropy state of a system, finds its roots back in the classical thermodynamics and the earliest formulations of the second law by Carnot and Clausius. The entropy as a macroscopic property of a system was then defined as a function of microstates via the statistical thermodynamics founded by Boltzman and further developed by Gibbs. An important step since it is their formulations which makes it possible to calculate exergy[3].

Exergy, $Ex$, is defined by the following equation[5]:

$$Ex = T_0(S_{eq} - S) \tag{1}$$

where $T_0$, $S$ are the temperature and entropy of the system respectively, $S_{eq}$ is the entropy of the same system at thermodynamic equilibrium.

For an open system with inorganic net inflow and passive organic outflow, self-organization will affect the concentration of component chemical species and, therefore, the chemical contribution to exergy content. Assuming that temperature and pressure of the system ($T$ and $P$) are the same as those of the environment ($T_0$ and $P_0$), exergy from Eq. (1) becomes:

$$Ex = RT\sum_{i=0}^{n}\left[C_i \ln\frac{C_i}{C_{i,eq}} - (C_i - C_{i,eq})\right] \tag{2}$$

in which $C_i$ and $C_{i,eq}$ are the concentration of the $i$th component in the far from equilibrium state and in thermodynamic equilibrium state respectively, $C_0$ is the concentration of the component in the inorganic matter, $R$ the gas constant and $T$ the absolute temperature[6]. By means of the above equation, Jorgensen[7] derived a formula to evaluate the exergy of ecosystems:

$$Ex/RT = (\mu_1 - \mu_{1,eq})\sum_{i=1}^{n}C_i/RT - \sum_{i=2}^{n}C_i \ln P_{i,a} \tag{3}$$

In Eq. (3), $\mu_1$ represents the chemical potential of detritus organic matter and $P_{i,a}$ is the probability to obtain a given component during the evolution by organizing organic matter according to information in

**Table 1 Approximate number of genes in organisms and exergy conversion factors**

| Organism | DNA/cell ($10^{-12}$g) | Number of genes | Conversion factor |
|---|---|---|---|
| Detritus | | 0 | 1 |
| Bacteria | 0.005 | 600 | 2.7 |
| Algae | 0.009 | 850 | 3.4 |
| Yeast | 0.02 | 2 000 | 5.8 |
| Fungus | 0.03 | 3 000 | 9.5 |
| Sponges | 0.1 | 9 000 | 26.7 |
| Jellyfish/Zooplankton | 0.9 | 50,000 | 143.9 |
| Fish | 20 | 120 000 | 344 |
| Field mouse | 50 | 140 000 | 402 |
| Human | 90 | 250 000 | 716 |

genes. Aminoacids in living organisms are 20 and each gene determines a sequence of 700 aminoacids, thus:

$$P_{i,a} = 20^{-700r} \tag{4}$$

($r$ = number of genes in the organism).

Therefore, the exergy can be calculated on the basis of existing studies on the evolution of DNA and genes in living organisms. Table. 1 gives some *average results for different organisms*[4].

Considering an aquatic environment, Eq. (3) and Table 1 yield a simple formula to calculate the global exergy of the system:

$$Ex = (1.79 \times 10^6)P + (104.9 \times 10^6)Z + (2.52 \times 10^8)F + (7.34 \times 10^5)(D + P + Z + F)(g/L) \tag{5}$$

in which $P$, $Z$, $F$ and $D$ are respectively the concentration (g/L) of phytoplankton, zooplankton, fishes and detritus organic matter. If the right hand of Eq. (5) is divided by the detritus exergy coefficient ($7.34 \times 10^5$), the same result expressed in grams of detritus equivalent can be obtained:

$$Ex = (1)D + (3.4)P + (144)Z + (344)F \text{(g detritus equivalent/L)} \tag{6}$$

Numbers in parentheses are conversion factors that give an approximate measure of the larger exergy contribution in $P$, $Z$ and $F$, in comparison with detritus exergy $D$. Conversion factors account for the information embodied in the organism, in addition to the exergy of the biomass itself.

It can be concluded that the higher the exergy of the system, the higher the distance of the system from thermodynamic equilibrium as well as the contribution that can be obtained from it when appropriately used[9], and different organizational levels could be measured by using their specific exergy content.

**2.2** The application of exergy in the development of structural ecodynamic model

In general, the model constraints should include the conservation principles, the chemical composition and the law of thermodynamics, however, only a few models can include the ecological constraints due to under-consideration of the properties of ecosystem. The thermodynamic concept "exergy" has the following advantages compared with other thermodynamic concepts: ①It is an energy term which is easily interpreted; ②Exergy is easily computed in the model; ③It is directly related to Darwin's theory and the application of exergy has therefore an ecological interpretation; and ④It is dependent on the environment, and is not a state variable as entropy, which makes it better fitted to be used in ecology.

According to Darwin's theory, all the species in an ecosystem have the properties (i.e. the set of parameters) that are best fitted for survival under the prevailing conditioins. The property of 'suivival' can be tested on the system level by use of exergy[2,10,11], so the set of parameters that gives the best survivors can be found. Jorgensen[12] proposed a parameter combination modelling procedure based on the maximum exergy principle and Darwin's theory (see table 2).

By application of exergy, the maximum exergy principle and Darwin's theory can be used to construct the above parameter combination modeling procedure, which allows a continuous development of the essential parameters of the model during simulation in accordance with the optimized function.

**Table 2　The parameter combination modeling procedure**

Select parameters in accordance with species composition

↓

Select most crucial parameters

$$P_1=(P_{11},P_{12},\cdots\cdots,P_{1m})$$

↓

Test after timestep $t_p$ all combinations of

$$P_i=\begin{cases}P_{i1}-x\%\\P_{i1}\\P_{i1}+x\%\end{cases}$$

and select the combination that gives the highest exergy to be used as

$$P_2=(P_{21},P_{22},\cdots\cdots,P_{2m})$$

for the timestep $t_p\rightarrow 2t_p$

↓

⋮

↓

Test after timestep $nt_p$ all combinations of

$$P_i=\begin{cases}P_{in}-x\%\\P_{in}\\P_{in}+x\%\end{cases}$$

and select the combination that gives the highest exergy to be used as

$P_{n+1}=(P_{(n+1),1},P_{(n+1),2},\cdots,P_{(n+1),m})$ for the timestep $nt_p\rightarrow(n+1)t_p$

## 3　Applications of structural ecodynamic model for lakes and reservoirs

Using the structural ecodynamic model proposed in this paper, the changes in ecosystems can be accounted for and the changes in ecological structure and species composition can be reflected by the changing model parameters and the changing exergy values[13].

In the study of Lake Dianchi[14,15], the ecological model proposed by Jorgensen[16] was selected as the basic model, exergy was introduced into the ecological model as a goal function of the maximum growth rate, settling rate of phytoplankton, the maximum growth rate of zooplankton to develop a structural ecodynamic model for Lake Dianchi, and parameter combinations were carried out by using the above modeling procedure. In Lake Dianchi, phosphorus is the main limiting factor of nutrients, so only the contribution to exergy from the phosphorus cycle was considered. In the study, exergy was computed using Eq. (2), the state variables included the concentrations of phosphorus in algal cells, soluble phosphorus, phosphorus in detritus and phosphorus in zooplankton. The results followed that this model can account for the changes in the ecological structure and species composition of lake ecosystem, and the changes in lake ecosystem can be reflected by the changing model parameters and the changing exergy values.

A structural dynamic model had been developed by Nielsen[3] in order to describe the shifts in composition of the phytoplankton society and tropic structures in a Danish shallow lake (Lake Vang) as response to changes in loading or biomanipulation. In this model, phosphorus was taken as the only limiting nutrient; the development of the phytoplankton society was chosen to be governed by a combination of the following factors: growth processes, loss processes, higher tropic levels, biological compartments (9 types of algae were included in the model: microcystis, aphanizomenon, stephanodiscus, asterionella, pediastrum, scenedesmus, dinobryon, peridinum and cryptomonas), the growth and the development of the phytoplankton society were governed by the grazing on phytoplankton and described as an ordinary Monod kinetic relationship and loss rate were included as an assimilation coefficient and excretion; the biological model was combined with a simple flow-ratio based hydrological model, chosen to be sufficient to simulate the hydrodynamics in this lake. The results indicated that exergy may play an important role in governing the development of the phytoplankton society.

Species composition often tells more about the condition of a lake or reservoir than water quality. The presence of blue-green algae or toxic algae is much greater environmental problem than a low transparency or a high nutrient concentration. In Jorgensen and Nielsen's[14] study, a two-classes phytoplankton model (diatoms and green algae) had been developed to try to predict the shifts in species composition between the dry and the rainy seasons. In this model, two nutrients were considered: phosphorus and silica. The settling rate for the diatoms was set to 0.5 m/d, but with a relation between the precipitation and the settling which will reduce the settling rate to 0.15m/d at the most rainy days. For green algae the settling rate was 0.2 m/d in the dry season with a reduction to 0.1 m/d in the rainy season. The results had shown that dominance of diatoms gave the highest exergy in the rainy season under the given circumstances (temperature, solar radiation, the stirring up effect of the rain and the retention time). Meanwhile, the distribution between the two classes of algae in the dry period gave the highest exergy.

In the study of Lake Glumso, exergy was used by Salomonsen and Jensen[17] as a measure of build-up of biological structure. Data from Lake Glumso for the period 1981-1984 were chosen for the study, in that period, the lake underwent a change in phytoplankton species composition. The study had shown that the two phytoplankton groups (chlorophytes and diatoms) did perform a larger build-up of exergy than if only one of the groups had been presented, and that the calibrated growth parameters for the chlorophytes represented the highest build-up of exergy while the results for the diatoms were less univocal.

In the study of Danish estuary, Roskilde Fjord, Nielsen[18] developed a structural model to simulate the structural dynamics of the macrophyte societies. The results have shown that it was possible to simulate the competition between the species and allow spatial coexistence through time in a very simple model based on growth capacity, light and temperature characteristics alone.

All the above studies have followed that exergy can be used as a goal function to develop the structural ecodynamic models for lakes and reservoirs to describe the shifts in the species composition and the changes in ecological structure of ecosystem, and used widely in the ecological modelling of lake environment.

## 4 Conclusions

The thermodynamic theories provide a holistic approach for capturing the properties of lake ecosystem, the thermodynamic concept "exergy" links well the ecological theory (Darwin' theory) with thermodynamic theory (the maximum exergy principle). By the application of exergy, a goal function of some important model parameters is obtained according to the maximum exergy principle, and Darwin's theory "survival of the fittest" can be quantified as an ecological constraint to develop the structural ecodynamic model for lakes and reservoirs, which makes the proposed model ecologically more reasonable and practically more flexible. However, it is of course still open question whether the procedure can be applied more generally and whether the development of this type of models requires that other factors are considered. The examination and optimization of exergy are still needed to discuss and study further.

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