Conservation Strategies for Endemic Fish Species Threatened by the Three Gorges Dam

YOUNG-SEUK PARK,*‡ JIANBO CHANG,† SOVAN LEK,* WENXUAN CAO,† SEBASTIEN BROSSE*

*LADYBIO, CNRS–Université Paul Sabatier, 118 route de Narbonne, 31062 Toulouse Cedex, France
†Institute of Hydrobiology, Chinese Academy of Sciences, 7 Southern Road of the East Lake, Wuhan 430072, China

Abstract: *The largest damming project to date, the Three Gorges Dam has been built along the Yangtze River (China), the most species-rich river in the Palearctic region. Among 162 species of fish inhabiting the main channel of the upper Yangtze, 44 are endemic and are therefore under serious threat of global extinction from the dam. Accordingly, it is urgently necessary to develop strategies to minimize the impacts of the drastic environmental changes associated with the dam. We sought to identify potential reserves for the endemic species among the 17 tributaries in the upper Yangtze, based on presence/absence data for the 44 endemic species. Potential reserves for the endemic species were identified by characterizing the distribution patterns of endemic species with an adaptive learning algorithm called a "self-organizing map" (SOM). Using this method, we also predicted occurrence probabilities of species in potential reserves based on the distribution patterns of communities. Considering both SOM model results and actual knowledge of the biology of the considered species, our results suggested that 24 species may survive in the tributaries, 14 have an uncertain future, and 6 have a high probability of becoming extinct after dam filling.*

Key Words: community patterning, endemic species, fish, reserve design, Three Gorges Dam

Estrategias de Conservación para Especies de Peces Endémicas Amenazadas por la Presa Three Gorges

Resumen: *El proyecto de represa más grande a la fecha, la Presa Three Gorges fue construida en el Río Yangtze (China), el río con mayor riqueza de especies en la región Paleártica. Entre las 162 especies de peces que habitan el canal principal del alto Yangtze, 44 son endémicas y por tanto están seriamente amenazadas de extinción global por la presa. Consecuentemente, es urgente desarrollar estrategias para minimizar los impactos de los cambios ambientales drásticos asociados con la presa. Tratamos de identificar las reservas potenciales para las especies endémicas entre los 17 afluentes en el alto Yangtze, en base a datos de presencia y ausencia de las 44 especies endémicas. Se identificaron las reservas potenciales para la especies endémicas caracterizando los patrones de distribución de especies endémicas con un algoritmo de aprendizaje adaptivo denominado "mapa auto-organizante" (MAO). Con este método, también predijimos las probabilidades de ocurrencia de especies en reservas potenciales en base a los patrones de distribución de las comunidades. Tomando en cuenta tanto los resultados del modelo MAO como el conocimiento actual de la biología de especies en consideración, nuestros resultados sugieren que 24 especies pueden sobrevivir en los afluentes, 14 tienen un futuro incierto y 6 tienen una alta probabilidad de extinguirse después del llenado de la presa.*

Palabras Clave: diseño de reserva, especies endémicas, modelo de comunidad, peces, presa Three Gorges

‡*Current address: Research Unit of Water Quality, Cemagref Bordeaux, 50 avenue de verdun, 33612 Cestas, France, email park@cict.fr*
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Introduction

River damming is the most dramatic anthropogenic factor affecting freshwater environments (Baxter 1977; Dynesius & Nilsson 1994; Dudgeon 2000). Dams cause habitat loss, change fish reproductive environments, and cut off migration routes, resulting in a substantial decline of biodiversity (Dynesius & Nilsson 1994; Dudgeon 2000; World Commission on Dams 2000).

The Three Gorges Dam (TGD), in the main channel of the upper Yangtze River, is the biggest hydroelectric dam in the world. The Yangtze supports 350 fish species (including 112 endemics); 261 species occur in the upper Yangtze alone (Chang 2001), representing the highest diversity in the Palearctic region (Nelson 1994; Matthews 1998). The Yangtze is therefore a crucial area for preserving fish genetic resources and biodiversity (Xie & Chen 1999). The TGD will entirely modify the main channel of the upper Yangtze, and 162 fish species (54% of the species of the upper Yangtze basin) will lose their natural habitats (Zhong & Power 1996; Chang 2001). Among these species, 44 endemics, such as the Yangtze sturgeon (*Acipenser dabryanus*), an emblematic living fossil species, are particularly threatened by the TGD (Dudgeon 1995; Chang 2001). Consequently, for the preservation of fish, particularly endemic species inhabiting the main channel of the upper Yangtze, conservation efforts must be made.

In practical conservation, surrogate information, such as richness of indicator taxa, endemism, or higher taxon richness, is used to identify possible conservation areas (Landres et al. 1988; Curnutt et al. 1994; van Jaarsveld et al. 1998). Distribution patterns of communities are typically derived from environmental conditions (Begon et al. 1996; Xie & Chen 1999) and species interactions (Harte et al. 1999; Brown et al. 2001). The regional features of species assemblages and the probability of occurrence of a given species in potential reserves are also considered in biodiversity conservation (Margules & Nicholls 1987; Pressey et al. 1993; Wahlberg et al. 1996; Margules & Pressey 2000).

Until now, the most frequently used statistical and modeling methods to identify species- or diversity-environment relationships have been based on linear principles (for review see James & McCulloch 1990). However, these approaches cannot overcome some significant biases due to both the complexity and the presumed nonlinearity of the data sets and inherent correlations among variables (Lek et al. 1996; Brosse et al. 1999, 2003). The self-organizing map (SOM) (Kohonen 1982), on the other hand, is efficient in dealing with systems ruled by complex nonlinear relationships and provides an alternative to traditional statistical methods (Lek et al. 1996; Lek & Guégan 2000). The SOM is an unsupervised neural network method that has been implemented in various ecological ways (Lek & Guégan 1999, 2000; Recknagel 2003): classification of communities (Chon et al. 1996; Park et al. 2001, 2003); identification of community patterns (Brosse et al. 2001); water-quality assessment (Walley et al. 2000; Aguilera et al. 2001); and prediction of population and community structure (Céréghino et al. 2001; Obach et al. 2001).

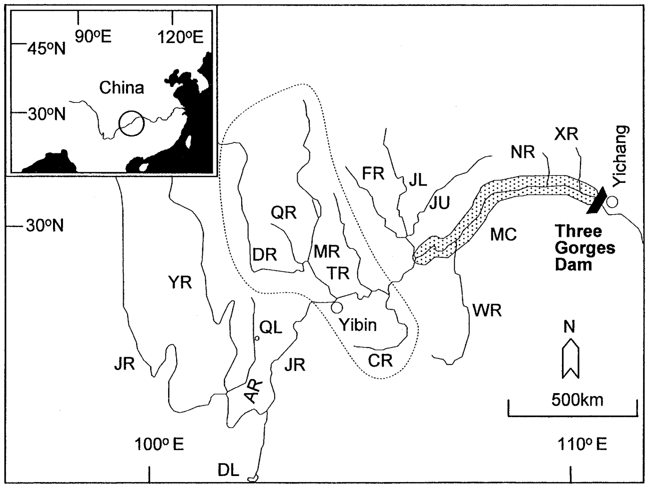


Figure 1. Study area of the upper Yangtze in China. Seventeen tributaries (including two lakes) were selected based on the presence of the endemic fish species found in the main channel (MC) of the upper Yangtze. The potential reserves are indicated with a dotted line. Tributary abbreviations are as follows: rivers Jinsha (JR), Yalong (YR), Anning (AR), Min (MR), Dadu (DR), Qinyi (QR), Tuo (TR), Chishui (CR), Jialing (JL), Fu (FR), Ju (JU), Wu (WR), Daning (NR), and Xiangxi (XR); lakes Dianchi (DL) and Qionghai (QL).

We used the SOM to characterize distribution patterns of endemic species living in the main channel of the upper Yangtze River. Then, model results allowed the identification of potential reserves (i.e., upper Yangtze tributaries) to sustain these species. Finally, occurrence probabilities of endemic fishes in potential reserves, as well as actual ecological knowledge about these species, were used to assess the vulnerability of each of them.

Methods

Data Set

The Yangtze is the third longest river in the world and the longest river in the Palearctic region. The main channel of the upper Yangtze is 1040 km long (Fig. 1). The TGD is located in the lower section of the main channel of the upper Yangtze. The resulting reservoir will flood over 600 km of the main channel, with a catchment area of 1.9 million km^2. It is predicted that the dam will be put into initial use in 2003 and filled by 2009. We collected data on fish assemblages in the 17 main tributaries of the upper Yangtze (Chang et al. 2002). Among the 350 fish species recorded, 162 fish species (including 44 endemics) are known in the main channel (Chang 2001; Chang et al. 2002). We focused on these 44 endemic species in the 17 tributaries in the upper Yangtze (Table 1), aiming to identify potential reserves. We used data on the presence or absence of endemic species to quantify their distribution in the tributaries and to predict the occurrence probability of each species.

Modeling Procedure

SOM Algorithm

The SOM is an unsupervised learning algorithm that simulates the hypothesized self-organizing processes carried out in the human brain when input data are presented (Kohonen 2001). The algorithm has properties of neighborhood preservation and local resolution of the input space proportional to the data distribution (Zurada 1992; Kohonen 2001). Therefore, it is widely applicable to the fields of data mining, data classification, and biological modeling in terms of a nonlinear projection of multivariate data into lower dimensions (Chon et al. 1996; Lek & Guégan 2000; Kohonen 2001; Park et al. 2003).

The structure of the SOM consists of two layers: an input layer formed by a set of units (or neurons) and an output layer formed by units arranged in a two-dimensional grid (Fig. 2). In this study, each input unit accounts for the presence or absence of one species in the 17 tributaries, leading to an input layer made of 44 neurons. The output layer was made of 20 output units in the hexagonal lattice (i.e., a grid of 5×4 cells), providing the best results with which to classify tributaries (Fig. 2). We preferred a hexagonal lattice because it does not favor horizontal or vertical directions (Kohonen 2001). Formally, the algorithm maps a set of input vectors (i.e., tributaries) onto a set of vectors of output units according to the characteristics of the input vector components (i.e., species). It can be interpreted as a nonlinear projection of the high-dimensional input data onto an output array of nodes. Here we assigned each tributary to one output unit as a result of the SOM algorithm calculation. Each output unit has a vector of coefficients associated with input data. The coefficient vector is referred to as weight (or connection-intensity) vector $\boldsymbol{W}$ between input and output layers. The weights play an important role in the propagation of the signal through the model. They establish a link between the input units (i.e., species) and their associated output units (i.e., groups of tributaries). The algorithm can be described as follows: when an input vector $\boldsymbol{X}$ (in this case, the presence or absence of 44 species in a given tributary) is presented to the network, the neurons in the output layer compete with each other and the winner (whose weight has the minimum distance from the input vector) is chosen. The winner and its neighbors, predefined in the algorithm, update their weight vectors according to the SOM learning rules, as follows:

$$w_{ij}(t+1) = w_{ij}(t) + \alpha(t) \cdot h_{jc}(t)[x_i(t) - w_{ij}(t)],$$

where $w_{ij}(t)$ is a weight between a neuron i in the input layer and a neuron j in the output layer at iteration time t, $\alpha(t)$ is a learning-rate factor that is a decreasing function of the iteration time t, and $h_{jc}(t)$ is a neighborhood function (a smoothing kernel defined over the lattice points) that defines the size of the neighborhood of the winning neuron (c) to be updated during the learning process. The explicit form of $h_{jc}(t)$ is as follows:

$$h_{jc}(t) = \exp\left(-\frac{\|r_j - r_c\|}{2\sigma^2(t)}\right),$$

where the parameter σ^2 (t) is a monotonically decreasing function of iteration time t defining the width of the kernel and $||r_j - r_c||$ is the distance in the output map between the winning neuron (c) and its neighbor neuron (j). This learning process is continued until a stopping criterion is met, usually when weight vectors stabilize or when a number of iterations are completed (Kohonen 2001). This learning process trains the network to pattern the input vectors and preserves the connection intensities in the weight vectors.

Map Quality Measures

After the SOM has been trained, it is important to know whether it has been properly trained. To do this, we computed a topographic error as an indicator of the topology preservation of the map (Kohonen 2001). This value represents the proportion of all data vectors for which first and second winner neurons are not adjacent for the measurement of topology preservation (Kiviluoto 1996).

On the trained SOM map, it is not easy to distinguish subsets because there are still no boundaries between possible clusters. Therefore, it is necessary to subdivide the map units into different groups according to the similarity of the weight vectors of the output neurons. We used a hierarchical cluster analysis with the Ward linkage method to define the cluster boundaries in the units of the SOM map and an analysis of variance (ANOVA) to compare the differences of species richness between clusters (and therefore tributaries) defined on the SOM map.

Visualization of Variables

Through the learning process, neurons that are topographically close in the SOM map activate one another to update their connection intensities (weights) from the same input vector. This results in a smoothing effect on the weight vectors of neurons. The weight vectors tend to approximate the probability density function of the

Table 1. Distribution of endemic fish species inhabiting the main channel of the upper Yangtze River.*

			Tributaries																
Order	*Family*	*Species*	*MC*	*JR*	*DL*	*YR*	*MR*	*QL*	*MR*	*DR*	*QR*	*TR*	*CR*	*JL*	*FR*	*JU*	*WR*	*NR*	*XS*
Acipenseriformes	Acipenseridae	*Acipenser dabryanus* Duméril	+	+					+			+	+	+		+	+		
Cypriniformes	Cobitidae	*Botia reevesae* Chang	+	+		+			+	+	+	+	+	+	+				
		Leptobotia elongata (Bleeker)	+	+		+	+		+	+	+	+	+	+	+	+	+	+	
		L.rubrilabris (Dabry)	+	+					+	+	+	+	+	+				+	
		Parabotia bimaculata Chen	+						+				+	+		+		+	
		Paracobitis potanini (Günther)	+	+		+	+		+	+	+	+	+	+	+		+	+	+
	Cyprinidae	*Abbotina obtusirostris* Wu & Wang	+	+					+	+	+	+							
		Acheilognathus omeiensis (Shih & Tchang)	+						+	+	+	+		+					
		Acrossocheilus monticola (Günther)	+						+		+	+	+	+	+		+		+
		Ancherythroculter kurematsui (Kimura)	+	+					+			+	+	+			+		
		A. nigrocauda Yih & Woo	+						+		+	+	+	+	+	+			
		A. wangi (Tchang)	+	+					+		+	+	+	+					
		Coreius guichenoti (Sauvage & Dabry)	+	+		+			+	+		+	+	+			+	+	+
		Gobiobotia abbreviata Fang & Wang	+						+		+	+	+						
		G. boulengeri Tchang	+	+					+	+	+	+	+	+	+	+	+	+	
		G. nudicorpa Huang & Zhang	+	+		+			+										
		Hemiculter tchangi Fang	+	+		+			+	+		+	+	+					
		Hemiculterella sauvagei Warpachowski	+						+	+	+	+	+	+			+		
		Megalobrama elongata Huang & Zhang	+																
		M. pellegrini (Tchang)	+	+		+	+	+	+	+	+		+	+	+	+	+	+	
		Onychostoma angustistomata (Fang)	+						+	+	+			+	+	+	+	+	
		O. brevis (Wu & Chen)	+																
		O. daduensis Ding	+							+									
		Percocypris pingi (Tchang)	+	+		+			+	+	+						+		
		Platysmacheilus nudiventris Lo, Yao & Chen	+						+		+		+	+					
		Procypris rabaudi (Tchang)	+	+		+	+	+	+	+		+	+	+	+	+	+		
		Rhinogobio cylindricus Gunther	+	+					+			+	+	+			+	+	
		R. ventralis (Sauvage & Dabry)	+	+					+	+		+	+	+			+	+	
		Schizothorax chongi (Fang)	+	+		+	+							+					
		S. prenanti (Tchang)	+	+					+	+	+	+	+				+	+	
		Sinibrama changi Chang	+						+	+	+		+						
		Sinilabeo rendahli (Kimura)	+	+		+			+	+	+	+	+	+	+	+	+		

Table 1. (continued)

Order	Family	Species	MC	JR	DL	YR	MR	QL	MR	DR	QR	TR	CR	JL	FR	JU	WR	NR	XS
		Tributaries																	
		Xenocypris fangi Tchang	+	+					+	+	+			+					
		X. yunnanensis Nichols	+	+	+				+					+					
		X. sechuanensis Tchang	+						+		+								
	Homalopteridae	*Beaufortia szechuanensis* (Fang)	+	+		+			+	+	+						+		+
		Hemimyzon abbreviata (Günther)	+	+		+	+		+	+	+		+	+	+				
		H. sinensis (Sauvage & Dabry)	+	+		+			+		+	+		+			+	+	
		H. yaotanensis (Fang)	+	+					+			+							
		Sinogastromyzon sichangensis Chang	+	+		+	+		+	+	+		+				+		
		S. szechuanensis Fang	+	+		+			+	+	+	+	+	+			+	+	
Perciformes	Gobiidae	*Ctenogobius szechuanensis* (Liu)	+											+					
Siluriformes	Sisoridae	*Euchiloglanis davidi* (Sauvage)	+	+		+	+		+	+	+	+		+					+
		E. kishinouyei Kimura	+	+					+	+	+	+		+			+		

**Presence of species in different tributaries is indicated by a plus (+) symbol. Abbreviations for tributaries are given in Fig. 1.*

input vector (Kohonen 2001). Therefore, the visualization of elements of these vectors for different input variables is a convenient way to understand the contribution of each input variable with respect to the clusters on the trained SOM. The connection intensity between input and output layers calculated during the learning process can be considered as the probability of occurrence for each species in the areas concerned. We placed these probabilities on the trained SOM map in gray scale to visualize the effects of each variable (i.e., species) on the patterning input dataset (i.e., tributaries) and to predict the potential occurrence probability for each species in the areas in which they were not collected during sampling. Based on the distribution pattern of the occurrence probability of each species, we selected potential reserves for endemic fish species that showed the highest occurrence probability. The highest occurrence probabilities of each species were then evaluated in the selected potential reserves. Once potential reserves were selected, we combined SOM model results concerning the predicted occurrence probability of the species in the reserves and available information on the life history of the species to estimate the conservation status of each species in the potential reserves (Table 2).

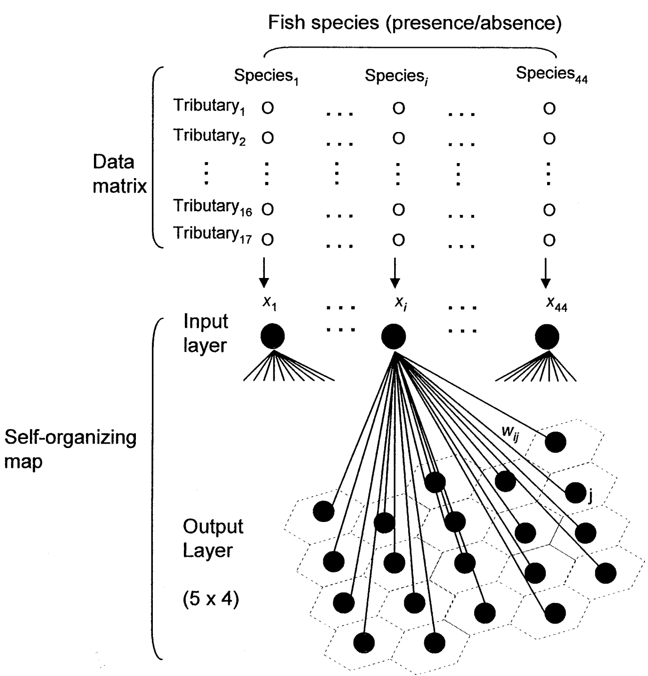


Figure 2. Schematic diagram of a self-organizing map (SOM). Data on presence or absence of 44 endemic fish species were sent into the input layer of the SOM as input data set for patterning their distribution in the tributaries and for predicting the occurrence probability of each species.

We used the functions implemented in the SOM toolbox (Alhoniemi et al. 2000) for Matlab (The Mathworks 2001) developed by the Laboratory of Information and Computer Science in the Helsinki University of Technology and adopted the initialization and training methods suggested by Alhoniemi et al. (2000) that allow the algorithm to be optimized. The functions can be implemented easily by an ecologist. The software library is free and available from http://www.cis.hut.fi/projects/somtoolbox.

Results

The topographic error calculated at the end of the unsupervised learning process was lower than 0.001. This

Table 2. Conservation status of the 44 endemic fish species inhabiting the main channel of the upper Yangtze River, based on a combination of available information on the ecology of the species and self-organizing map (SOM) model results.

Species	Commercial interest[a]	*Information derived from species life history*[b]					Conservation status in the reserves[d]
		migratory	spawning	larval nursery	probability of completing life cycle	SOM model prediction[c]	
Acipenser dabryanus	no (protected)	yes	M	M	low	high	EX
Botia reevesae	no	no	M & T	M & T	high	high	SU
Leptobotia elongata	yes	yes	M	M	low	high	EX
L. rubrilabris	no	no	M & T	M & T	high	high	SU
Parabotia bimaculata	no	no	M & T	M & T	high	high	SU
P. potanini	no	no	M & T	M & T	high	high	SU
Abbottina obtusirostris	no	no	M & T	M & T	high	high	SU
Acheilognathus omeiensis	no	no	M & T	M & T	high	high	SU
Acrossocheilus monticola	no	no	M & T	T	high	high	SU
Ancherythroculter kurematsui	yes	no	M & T	M	unknown	high	TH
A. nigrocauda	yes	no	M & T	M	unknown	high	TH
A. wangi	yes	no	M & T	M	unknown	high	TH
Coreius guichenoti	yes	yes	M	M	low	high	EX
Gobiobotia abbreviata	no	no	M & T	M & T	high	high	SU
G. boulengeri	yes	no	M & T	M	unknown	high	TH
G. nudicorpa	no	no	M & T	M & T	high	median	TH
Hemiculter tchangi	yes	no	M & T	M & T	high	high	SU
Hemiculterella sauvagei	no	no	M & T	M & T	high	high	SU
Megalobrama elongata	no	no	?	?	unknown	low	EX
M. pellegrini	yes	no	M & T	M	unknown	high	TH
Onychostoma angustistomata	no	no	M & T	T	high	high	SU
O. brevis	no	no	?	?	unknown	low	EX
O. daduensis	no	no	M & T	T	high	median	TH
Percocypris pingi	no	no	M & T	M & T	high	high	SU
Platysmacheilus nudiventris	no	no	M & T	M & T	high	high	SU
Procypris rabaudi	yes	no	T	M	unknown	high	TH
Rhinogobio cylindricus	yes	no	M	M	unknown	high	TH
R. ventralis	yes	no	M	M	unknown	high	TH
Schizothorax chongi	no	no	T	T	high	median	TH
S. prenanti	no	no	T	T	high	high	SU
Sinibrama changi	no	no	M & T	M & T	high	high	SU
Sinilabeo rendahli	yes	no	?	?	unknown	high	TH
Xenocypris fangi	no	no	M & T	M & T	high	high	SU
X. yunnanensis	no	no	M & T	M & T	high	high	SU
X. sechuanensis	no	no	M & T	M & T	high	median	TH
Beaufortia szechuanensis	no	no	M & T	M & T	high	high	SU
Hemimyzon abbreviata	no	no	M & T	M & T	high	high	SU
H. sinensis	no	no	M & T	M & T	high	high	SU
H. yaotanensis	no	no	M & T	M & T	high	median	TH
Sinogastromyzon sichangensis	no	no	M & T	M & T	high	high	SU
S. szechuanensis	no	no	M & T	M & T	high	high	SU
Ctenogobius szechuanensis	no	no	M & T	M & T	high	low	EX
Euchiloglanis davidi	no	no	M & T	M & T	high	high	SU
E. kishinouyei	no	no	M & T	M & T	high	high	SU

[a] *Sources: Chang 2001, Ke et al. 2001, and Chang et al. 2002.*
[b] *The migration status indicates the fish that migrate between upper and lower Yangtze to complete their life cycle. Migratory species were considered to have a low probability of completing their life cycle in the reserves. Species having spawning grounds and/or larval nurseries located only in the main channel were considered to have an unknown probability of completing their life cycle in the reserves. Abbreviations: M, main channel; T, tributaries.*
[c] *The SOM model prediction indicates the probability* (p) *of each species establishing in the potential reserves derived from the SOM analysis (high,* $p > 0.6$*; median,* $0.6 > p > 0.3$*; low,* $p < 0.3$*).*
[d] *Abbreviations: EX, close to extinction; TH, threatened; SU, may be sustained in the reserves.*

value means that the first and second winning neurons (the best matching units) were adjacent for all samples patterned in the SOM, testifying that the SOM map was relevant (Kiviluoto 1996; Kohonen 2001) and therefore provided a realistic pattern of the tributaries. The SOM pattern identified three groups of tributaries according to the distribution characteristics of endemic species (Fig. 3a & 3b). The species richness of endemics differed

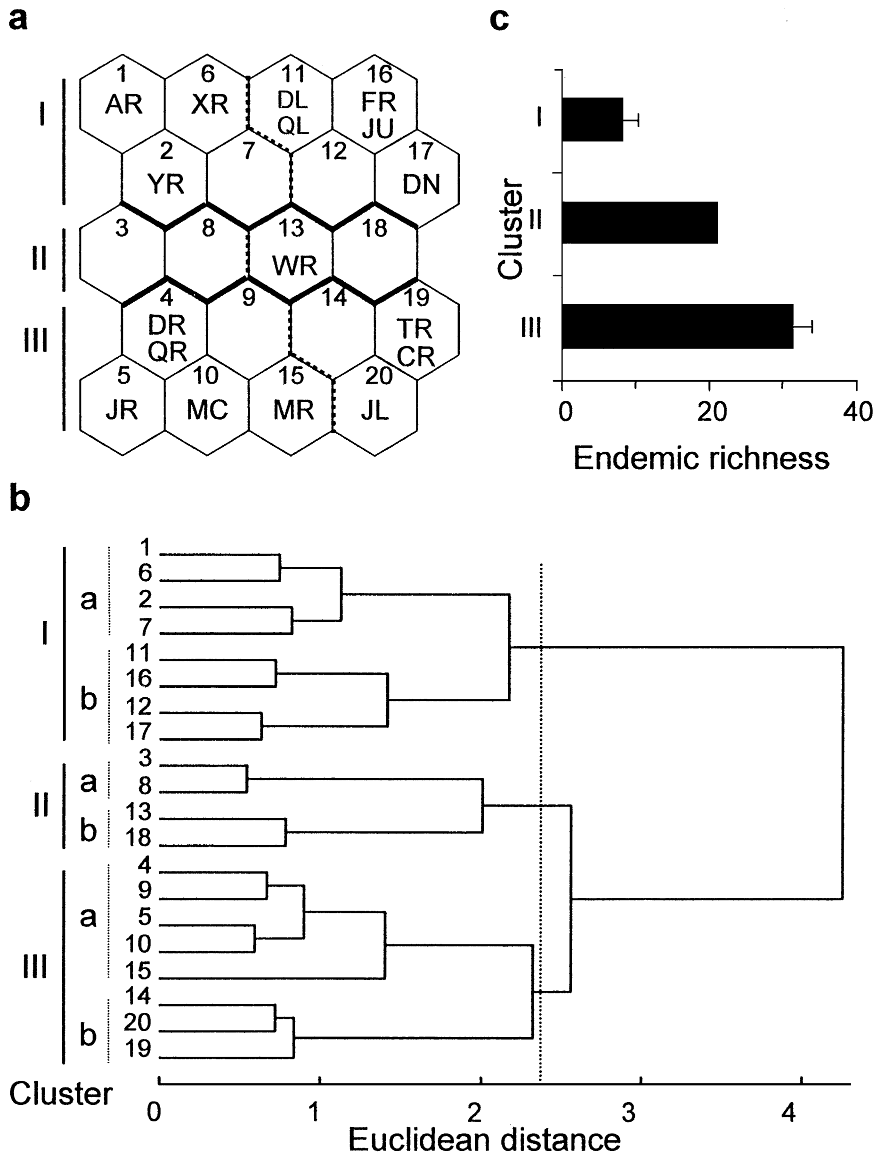
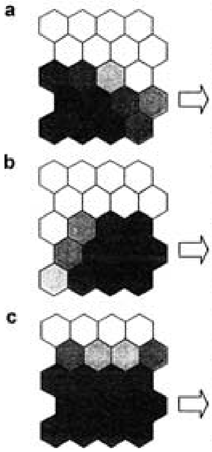


Figure 3. Classification of Yangtze tributaries based on the self-organizing map (SOM).(a) The patterned SOM map. The tributaries (abbreviations defined in Fig. 1) were patterned by means of the SOM with endemic species. Then, they were classified into three clusters based on a hierarchical cluster analysis (b). The three clusters are marked off with bold vertical lines, and their subgroups are separated with dotted lines. (b) Hierarchical classification of the SOM map. The numbers (1–20) correspond to those in units of (a). There are three clusters with subgroups. (c) Mean species richness calculated for each cluster. Error bars display standard errors. Endemic richness differed significantly between clusters (analysis of variance, $p < 0.001$*).*

significantly among three clusters (analysis of variance, $p < 0.001$), indicating strong gradients in the distribution (Fig. 3c). Tributaries located in the upper areas on the SOM (cluster I) represented the lowest diversity of endemic species (<9 species), whereas those in the bottom areas (cluster III) accounted for the highest diversity (>31 species). Tributaries with intermediate diversity (cluster II) were in the middle area of the map (21 species).

Using a qualitative dichotomous (presence/absence) data set of endemic species, the model calculated quantitative continuous values between 0 and 1. The occurrence probability of each species in a given tributary in the form of the connection intensity was visualized on the SOM map to analyze the effect of each species on distribution patterns in the corresponding areas. It was then possible to predict the probability of each species being present where it was not actually collected. The tributaries of cluster I did not constitute appropriate potential reserves for endemic species because the species had low probabilities of occurrence, whereas tributaries classified in cluster III revealed high reserve potential with high probabilities of species' occurrence (Figs. 3 & 4). Considering this last cluster, three species groups could be identified according to the distribution patterns on the SOM map: 22 and 16 species had high probabilities of occurrences in the lower left areas (Fig. 4a) and in the lower right areas (Fig. 4b), accounting for clusters IIIa and IIIb, respectively. Similarly, the remaining 6 species had high occurrence probabilities in both lower left and lower right areas (Fig. 4c). Therefore, each species had its own occurrence probability in a given habitat, and there are two different kinds of potential reserves for the endemic species living in the main channel of the upper Yangtze. Accordingly, the tributaries classified into these two parts can be considered potential reserves for the conservation of endemic fish species in the main channel.



Endemic fish species	Cluster
Abbotina obtusirostris (Abb), *Acheilognathus omeiensis* (Ach), *Beaufortia szechuanensis* (Bea), *Botia reevesae* (Bot), *Coreius guichenoti* (Cor), *Euchiloglanis davidi* (Eud), *E. kishinouyei* (Euk), *G. nudicorpa* (Gon), *Hemiculter tchangi* (Het), *Hemimyzon abbreviata* (Hea), *Megalobrama elongata* (Mee), *M. pellegrini* (Mep), *Onychostoma brevis* (Onb), *O. daduensis* (Ond), *Paracobitis potanini* (Pap), *Percocypris pingi* (Per), *Schizothorax chongi* (Scc), *Sinibrama changi* (Sic), *Sinogastromyzon sichangensis* (Sis1), *Xenocypris fangi* (Xef), *X. sechuanensis* (Xes), *X. yunnanensis* (Xey)	IIIa
Acipenser dabryanus (Aci), *Acrossocheilus monticola* (Acr), *A. kurematsui* (Ank), *A. nigrocauda* (Ann), *Ctenogobius szechuanensis* (Cte), *G. boulengeri* (Gob), *H. yaotanensis* (Hey), *Leptobotia elongata* (Lee), *L. rubrilabris* (Ler), *O. angustistomata* (Ona), *Parabotia bimaculata* (Pab), *Platysmacheilus nudiventris* (Pla), *Procypris rabaudi* (Pro), *Rhinogobio cylindricus* (Rhc), *R. ventralis* (Rhv), *Sinilabeo rendahli* (Sir)	IIIb
Schizothorax prenanti (Scp), *S. szechuanensis* (Sis2), *Ancherythroculter wangi* (Anw), *Gobiobotia abbreviata* (Goa) *Hemiculterella sauvagei* (Hes1), *H. sinensis* (Hes2)	III

Figure 4. Distribution patterns of endemic fish species among tributaries. Grey-scale gradients account for probabilities of occurrence, with dark corresponding to high probability and light to low probability. (a) and (b) correspond to clusters IIIa and IIIb in Fig. 3, respectively. Twenty-two species are assigned to group (a) and 16 species to group (b). The remaining six species show a high probability of occurring in both areas (c).

The Jinsha and Min rivers (including the Dadu and Qinyi rivers) in cluster IIIa could constitute reserves for 28 endemic species (i.e., 22 in Fig. 4a and 6 in Fig. 4c), including *Abbotina obtusirostris*, which display high probabilities of colonizing these areas (Figs. 3a & 4a). In the same way, the tributaries Jialing, Tuo, and Chishui in cluster IIIb may be a potential refuge for 22 endemic species (i.e., 16 in Fig. 4b and 6 in Fig. 4c), including *Acipenser dabryanus* (Figs 3a & 4b). As expected, some species may also survive in both areas.

Among these tributaries, we calculated the probability of occurrence of each fish species in selected reserves (Fig. 5a & 5b), showing that 8 fish species have a probability lower than 0.6 of establishing in the reserves. Although the model predicted that more than 80% of the endemic fishes have a high probability of establishing in the reserves (Fig 5c), actual knowledge of life histories reveal that at least 12 additional species may not be able to complete their life cycle after the dam fills. Combining model predictions and biological knowledge (Table 2) revealed that 24 species may establish in the tributaries, 14 have an uncertain future, and 6 have a high probability of becoming extinct after the dam fills, even if suitable reserves are selected.

Discussion

The impact of river damming on aquatic ecosystem functioning has been documented (Baxter 1977; Allan 1996 for review). Although the most dramatic ecological impacts of dams are identified downstream as a result of water-flow regulation and fragmentation of the river continuum (Baxter 1977; Dynesius & Nilsson 1994; Dudgeon 2000), ecological impacts on upstream fish populations have rarely been investigated except for migratory fishes (Allan 1996; Helfman et al. 1997). It is well known, however, that the environmental changes occurring in reservoirs, on the shift from a free-flowing environment to stagnant water ruled by different biological processes, deeply influences fish populations, even nonmigratory ones. For example Minckley and Deacon (1991) reported that dam construction in the Colorado River threatened most of

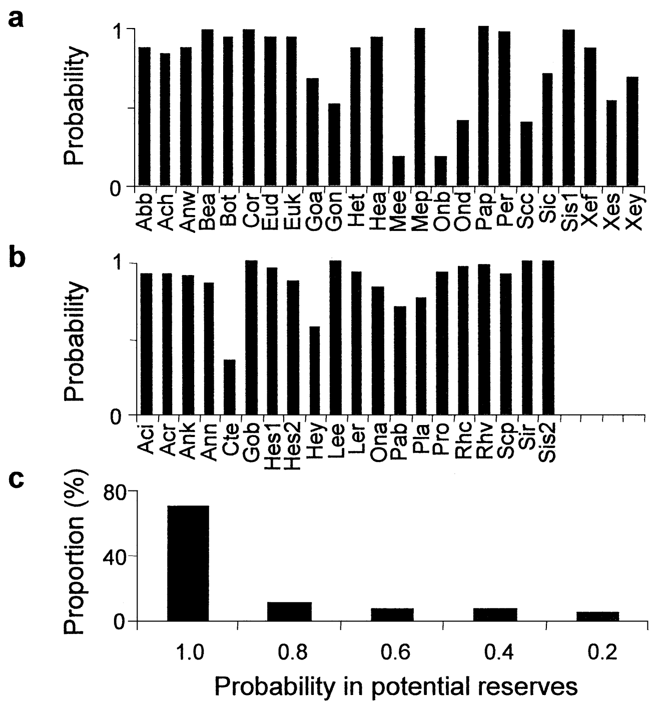


Figure 5. Predicted probability of occurrence of fish species in potential reserves. The probability was predicted for each endemic species to become established in potential reserves assigned in (a) Min River basin (cluster IIIa in Figs. 2 & 3) and (b) Tuo and Chishui river basins (cluster IIIb in Figs. 3 & 4). Species abbreviations are defined in Fig. 4. (c) Frequency of the probability of occurrence.

the native freshwater fishes and favored only a few generalist exotic species. In the same way, dams on large rivers, such as the Aswan High Dam on the Nile River, and several dams along the Volga River, have caused a dramatic decline of fish diversity and abundance (Welcomme 1985; Moyle & Leidy 1992). According to Dudgeon (2000), the TGD will probably have a considerable impact on upper Yangtze fish populations, and fish reserves should quickly be set aside to sustain Yangtze fish diversity.

According to the SOM analysis in this study, some tributaries might constitute appropriate potential reserves for the endemic fish species (cluster III, Figs 3 & 4). The results should be interpreted with caution, however, because some tributaries, although predicted to be suitable refuges, may not be appropriate as actual reserves as a result of intensive human activities and damming following the development scheme of the Yangtze basin (Changjiang Water Resources Commission 1999). These future dams will reduce flow and modify thermal regime and water quality, as has happened with large dams around the world (Baxter 1977; Allan 1996; Helfman et al. 1997). Therefore, although suitable reserves exist at the present time, planned environmental changes might greatly modify their reserve status. In this way, the tributaries Jinsha and Jialing may not constitute sustainable reserves because the Chinese government has already planned to build more than 10 hydropower dams on the Jinsha River. Two of these dams (Xiluodu and Xiangjiaba) will be constructed soon after the TGD has begun to fill in 2003. Similarly, there is also a large development scheme for hydropower on the Jialing (Changjiang Water Resources Commission 1999). In addition, the Jialing basin is located at the end of the reservoir and could be affected by the TGD because it will be separated from the other tributaries by the reservoir. Thus, these tributaries cannot be considered potential natural reserves for endemic fishes. Consequently, we can only consider tributaries in the Chishui, Tuo, and Min basins as potential suitable reserves for endemic species living in the main channel; these tributaries are indicated as dotted lines in Fig. 1.

This reserve selection is also supported by the fact that the distribution and composition of fish species recorded in these tributaries are close to those of the main channel, and their environmental status is similar to that of the main channel. For example, the Chishui is inhabited by 109 fish species, including 26 endemic species (Chang 2001), and all these endemic species are also found in the main channel, accounting for about 60% of the main channel's endemic species. Consequently, these selected tributaries are suitable locations for establishing the first river reserves for endemic fishes in China. Based on this reserve selection, we predicted the probability that each species can establish itself in these areas from the connection intensities of the SOM (Fig. 5a & 5b). The mean probability of occurrence was >0.8 (SD = 0.23); consequently, more than 80% of the endemic species have a probability of >0.6 of successfully establishing in the potential reserves (Fig. 5c). However, some species had relatively low probabilities of occurrences. Three species in particular, *Megalobrama elongata*, *Onychostoma brevis*, and *Ctenogobius szechuanensis*, displayed probabilities lower than 0.3. They have limited distribution in the upper Yangtze and are only found in the main channel. Therefore, they are more threatened than other species. *O. brevis* was not observed in the field investigations, and its population has become weaker (Chang et al. 2002). As a consequence, these three species have a high probability of becoming extinct after TDG filling.

Although the model predicted that most endemic species have a high probability of establishing in the reserves, we should keep in mind that due to the limited ecological data on Yangtze endemics, occurrence probability was derived from presence and absence data, and fish life cycles were not taken into account. Although the model provided relevant information on potential reserve selection, fish biology provided complementary information on the sustainability status of some species (Table 2). In that way, three species are particularly threatened as they migrate between upper and lower Yangtze for reproduction (Table 2) (Chang 2001). Although predicted as being able to establish in the reserves, and although the physical environment of the reserves matches the ecological requirements of these species, it is not actually possible to predict whether they will be able to complete their life cycle in the upper Yangtze. Among these three species, *Leptobotia elongata* and *Coreius guichenoti* constitute an important resource for local fisheries and are under local protective law (Jiang et al. 2001). The third species, *Acipenser dabryanus*, is an emblematic species listed in the World Conservation Union's (IUCN) Red List of Threatened Species (World Conservation Union 2002). In addition, 9 other species are known to achieve their life cycle using the main channel as spawning sites and/or nursery areas, and 5 more species have a probability of <0.6 of establishing in the reserves (Table 2). Once again, model predictions should be carefully verified for these species because although the potential reserves constitute a suitable environment for these species, their future is still uncertain, and the biology and life history of these species is still poorly known. This signifies that, despite hypothetical conservation efforts, among the 44 endemic species living in the main channel of the upper Yangtze, 6 protected and commercially important species have a high probability of becoming extinct, 14 have an uncertain future, and 24 may establish in the reserves. Moreover, among the 12 endemic fishes of commercial interest, 10 are threatened by the TDG (Table 2). In addition to the loss of biodiversity, the changes in the fish community caused by the dam may also reduce fish resources for local people.

After the TGD is filled, the fish populations that will establish in tributaries may modify current species assemblages and food webs (Chapin et al. 2000), as experienced with the introduction of exotic species in many lakes and rivers around the world (Matthews 1998). We did not consider these possibilities because of the lack of ecological information, but they may affect the probability some endemic species have of becoming established in the reserves. In this context, the potential of the tributaries we studied to act as reserves for endemics urgently needs to be verified in the field before a conservation plan is set up.

The TGD will have dramatic impacts on the ecosystems of the Yangtze River. The results of this paper alert the scientific community to the threats faced by the Yangtze, as well as numerous large rivers around the world. Three Gorges Dam construction is about to be completed, and we now have to deal with this ecological disaster. Selecting appropriate reserves, although making the best of a very bad situation, is the only means of protecting endemic fishes of the upper Yangtze. Selecting appropriate tributaries as reserves should save some endemic species and help protect these areas from other dam construction projects, contributing to the preservation of the entire freshwater ecosystem.

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