Tonle Sap Ecosystem Fish Species Biological Groups and Hydroecological Index

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ABSTRACT

The Tonle Sap ecosystem in the lower part of the Mekong River basin is influenced by hydrological regimes of the Mekong River. The change of lake water level from 1 to 14 m is considered strongly influencing the hatching and feeding grounds of Tonle Sap fish communities. Identifying the hydrological parameters that possibly influenced fish community to develop a hydrolecological index and this index would be used as the monitoring tool to assess the relationship between hydrological regime and fish production in the Tonle Sap ecosystem is the aim of this study. Four k and r-strategist fish groups were classified by clustering analysis based on nine biological attributes. A trophic model of the Tonle Sap ecosystem fish community was initially drawn based on the correlations among 24 dominant species. By the multi-parameter analysis, five parameters, namely “average drought inundated area”, “drought duration” “maximum flood inundated area”, “receding duration”, and “flood timing” were identified from eight potential hydrological parameters. The values of each selected parameter was categorized into three groups and assigned a set of scores of 1, 3 and 5 based on two thresholds lower ai and upper bi and narrated as poor, fair and good conditions respectively. The yearly hydroecological score was calculated from those parameter scores in relative year. The hydroecological index scores were highest (5) in year 2000 and lowest (1) in year 1998 during period 1995-2002. The inundated area and flood timing were the most factors that influence fish production. Importantly, the constituted hydroecological index was significantly correlated (P<0.05) with bag net fish catch in year y and k (group 2) fish species in year y+1 indicating that the index was a potential monitoring tool to be used to assess the relationship between hydrological regimes and fish production and to support for hydropolicy decisions.

Keywords: Tonle Sap ecosystem, hydroecological index, bag net fishery, fish biological attribute, k and r strategist, trophic model and multi-parameters analysis.

INTRODUCTION

The Tonle Sap (TS) ecosystem, including the TS River and the TS Great Lake in the central part of Cambodia, is situated in the lower part of the Mekong River basin (MRB) (Fig 1). This ecosystem is well known as the largest wetland having the highest biodiversity in Southeast Asia (Mok et al 2001). A total of 197 phytoplankton, 46 zooplankton and 57 zoobenthos species (Nguyen and Nguyen 1991), 146 fish species from the water and 200 species of tall trees in the TS lake floodplain have been recorded (Ian et al 2005). The lake functions as the hatching and feeding grounds for both the migrant and non-migrant fish species (Sarkklua et al 2003). The TS ecosystem supports the fourth most productive captive fishery in the world (Rainboth 1996) and contributes approximately 60% of the total inland catch of Cambodia (Csavas et al 1994 and WB 1995). The total annual catch, which includes rice field fishing and family scale operations, is estimated to range between 177,000 and 400,000 tons (Van Zaling and Thouk 1999 and Van Zalinge et al. 2003). This fisheries production contributes 60% of the protein intake of the entire Cambodian population, and is of particular importance to the over one million poor people living surrounding the TS Lake (Ahmed et al. 1998), where the average fish consumption is approximately 65.6 kg per capita annually (Keskinen 2003).
The complexity of a rive-floodplain pulsing system in the TS ecosystem is similar to that of central Amazon floodplain that is detail discussed by Junk (1997). The hydrology of the TS ecosystem is mostly determined by over 4000 km long of the upper Mekong River, 60% of the volume of the lake water is supplied from the Mekong River (Mekong Secretariat 1992 and Hak and Piseth 1999). The water level of the TS Lake can rise up to a depth of 14 m at the maximum peak in the wet season (Jun-Oct) due to the inflow from the Mekong River, and it can recede to a depth of 1 m during the dry season (Nov-May), as the water from the lake recedes into the Mekong Delta (Mekong Secretariat 1992 and Hak and Piseth 1999). This extensive flooding enables the lake to expand from a minimum size of approximately 2,500 km2 to over 10,000 km2 and up to almost 16,000 km2 of the lake surface area (Mok et al 2001 and MRC 2003). The lake can store approximately 72 Gm3 of water annually (Hak and Piseth 1999) and drains an area of 85,065 km2 of the Mekong Delta during a 5-6 month dry season (Mekong Secretariat 1992).

There is a high demand for water resources for hydropower, irrigation of agriculture and water supply to the 65 million people within the MRB (Chu et al 2003). Of the 40 hydropower dams with an over 10 megawatt capacity within MRB, 13 have been operating since 2001 (MRC 2003); of these, the two largest dams are located in the main upper Mekong River in China (Kristensen 2001). The constructed dams have led to water abstraction diversion, trapping of sediments and increased water evaporation (MRC 2003) resulting in a reduction in water flow. Although, approximately 5% of the annual flow of the Mekong River is regulated by dams (Piper et al 1991), these dams modify streams by changing the timing, duration and quantity of flooding further downstream (MRC 2003). This may cause loss, modification or fragmentation of aquatic habitats, resulting in the disconnection of fish migration routes (MRC 2003). Dams often reduce the extent of downstream flooding and thereby reduce the extent of the connectivity between adjacent river systems, with consequences for the genetic structure of regional fish production (Arthington 2004). For example, after the construction of the Nam Song weir in Laos in MRB, 40 fish species disappeared from the catches in the surrounding areas of the weir and 20 transboundary migratory fish species were lost from catches in the neighbouring countries (MRC 2003). In the Cinaruco River, Venezuela, the fish species composition and assemblage structure are significantly correlated with the depth of site and time of the inundation period (Hoeinghaus et al. 2003). To protect the freshwater biodiversity, the studies of the magnitude, frequency, timing, duration, rate of change, flood and drought are necessary (Arthington et al. 2006).

In the Tonle Sap ecosystem, because of the great fluctuation in hydrological conditions (e.g., seasonal changes in the water depth in the TS Lake), it is expected that the productivity of the TS ecosystem is significantly related to the hydrological parameters. The importance of hydrological condition for fish life history and production in the TS ecosystem was proposed by Baran and Cain (2001), Baran et al (2003) and Welcome and Halls (2003) is as follows: (i) flood timing is important for many fish species that spawn in the flooded area. The maturation and flood phase have to be synchronized particularly for species having one shot of spawning. (ii) The discontinuity of the floods may influence the migratory fish species. The discontinuity may impede spawning and recruitment of larvae in the floodplains. (iii) The change rate of the rising water can affect the fish hatching habitats, because the hatching habitats are rapidly submerged to too great depths; additionally, the rapidly receding water can increase the risks of standing fish in the temporal pools and channels of the floodplain. (iv) The flood duration influences the time available for the fish to grow and shelter themselves from predators in shallow floodplains. (v) The longer the duration of the dry season, the greater is the stress to most of the river fish species, while a higher water level during the dry season provides the more refuge for the fish.

Three major fisheries in the TS ecosystem include bag net (Dai) fishery in the TS River in the lower part of the ecosystem, lot fishery in the floodplain areas and middle scale fishery in the open lake. Lot fishery is characterized a numerous hectares located in the floodplain and using kilometer-long of fences and killed room at the end of the floodwater receding season. The area of lot fishery was not changed during 1995-1999. Middle scale fishery is characterized by mobile fishing gears such as gillnets, traps, etc. The number of fishing gears has been rapidly increasing. The middle scale fish catches were basically estimated based on fishing effort and catch per unit effort. Bag net fishery in the TS River is a big and stationary net with a mouth opening up to 27 m in diameter and 4 cm of mesh size and stretching 150 m in length and 1.5 cm of mesh size at the end of the bag. It is operational from Oct or Nov to Feb or Mar to sweep the migratory fish species along their migration routes from the TS Lake and upstream floodplains to downstream in the Mekong Delta during floodwater receding duration. The number of bag nets is regulated by CDoF: there were 63 days allocated in 15 rows annually during the period 1995-2002. Thus, the catch of bag net in a given year is likely to reflect the fish productivity during that year. Therefore, bag net fishery is possibly a good indicator of fish productivity in the TS ecosystem. The positive correlations between maximum water level at Kampong Luong station (Fig 1) and the annual total bag net fish catch and or “white” and “opportunist” fishes have been reported.
by Lieng et al (1995) and Van Zalinge et al (2003). Note that “white” fishes was classified as a group of species that mainly associated with the main channels and stream, but also migrate into the floodplain and the “opportunist” fish was classified as small, fast-growing and prolific species, able of utilizing the flood period for prolific reproduction and/or growth (Mekong Secretariat 1992). To better understand the natural complexity of the TS ecosystem and to illustrate the influence of the hydrological regime in relation to fish habitats and life history, and subsequently on fish production in this ecosystem, a multidimensional analysis of the several ecologically relevant hydrological parameters is necessary. A method to analyze the multi-relationship among hydrological parameters for the redundancy and choice of the hydrological index by using principal component analysis (PCA) was introduced by Olden and Poff (2003). The objectives of this study are 1) understanding the TS ecosystem fish community and classifying fish species into biologically different groups, which can sensitively respond to different levels of environment; 2) identifying the potential hydrological parameters that possibly influence fish community and further constituting a hydroecological index (HEI) that can be used as the monitoring tool and 3) validating the applicability of the HEI by testing the response of fish production to this index.

METHODS

The schematic of the TS ecosystem fish community studies and hydroecological index development were shown in Fig. 2. The biological attributes of the fish species found in the fish statistics of the TS ecosystem were obtained from the FishBase information system (Froese and Pauly 2006). In order, to avoid the more weightage of a given biological attribute in fish group classification, then only one representative attribute of a group that included some similar attributes was selected. For example, only maximum length was representative selected from five similar attributes including maximum length, maturity length, infinity length, yield length and length-weight. There were no representative attributes from exploitation rate and reproduction because of no data available of these attributes. A set of nine selected biological attributes included maximum length, growth coefficient, natural mortality, life span, age at the first maturity, resilience, main food, trophic level and food consumption. The similarity of the set of these nine biological attributes was used to classify fish species into $k$ and $r$ strategist groups. The $k$-strategists are large and slow-reproducing and growing fishes that produce few offspring and have a high energy demand. In contrast, $r$-strategists are small and fast-reproducing and growing fishes that produce many offspring and have a low energy demand (Chapman and Reiss 2000). The lot and middle scale fisheries data during 1995-1999 and bag net fishery during 1995-2005 provided by MRC (Mekong River Commission) and CDoF (Cambodia Department of Fishery) were used to analyze the spatiotemporal fish species compositions and catch proportions. Because the number of bag nets in the TS River and the area of lot in the floodplain were not changed during 1995-1999, then the $k$ and $r$ fish species of the bag net and lot fisheries during 1995-1999 were used to analyze and illustrate the trophic model of fish community in the TS ecosystem. While the bag net fish catches during 1995-2002 was used to test the sensitiveness of HEI and hydrological parameters in reflecting fish production to evaluate the applicability of HEI.

![Figure 2. Schematic of the TS ecosystem fish community studies and hydrological index development.](image-url)
components of the PCA were selected and combined to obtain the index. Because the water level was used to calculate the inundated area, henceforth, the inundated area parameter would be alternatively selected to constitute the HEI instead of water level, in case; both were high correlation coefficients on the PCA. The cumulative distribution analysis, wherein all the values of a given parameter are projected in an ascending order, was used to identify the lower (ai) and upper (bi) parameter threshold values. These threshold values enabled to classify parameter yearly values into three groups which representing three different conditions of hydrology. A set of scores 1, 3 and 5 were given for each parameter value groups and narrated as poor, fair and good conditions respectively. However, the set of scores assigned increase or decrease in accordance with the increase of each parameter values were based on the positive or negative correlation of that parameter with fish production in the sample period. The HEI of a given year was calculated by the average of all parameter scores in that year and the number (n) of parameters as follows: HEI = (Score parameter 1 + Score parameter 2 ... + ... Score parameter n)/n. The Pearson correlation tests were used to test 1) the correlation coefficient of each pairwise of two given species productions to identify the predator-prey relationships and 2) the correlation coefficient between HEI and fish catch and the k and r fish biological groups to evaluate the sensitiveness of the HEI in reflection fish production of the TS ecosystem.

RESULTS

**Tonle Sap ecosystem fish community studies.**

A total of 178 fish species from 35 fish families, including 154 species found in bag net fishery during 1995-2002 and 70 and 45 species found in lot and middle scale fisheries respectively during 1995-1999, were classified into four biological groups in the rank of k and r-strategists based on nine fish biological attributes of the TS and Mekong River ecosystems by clustering analysis at 85% of similarity on dendrogram (Fig.4a) and 0.11 coefficient in NMDS (Fig.4b). Three species, namely *Clupisoma longianalis*, *Pangasius djambal* and *Trichogaster trichopterus*, were ungrouped from the four major groups (Fig.4b). In Fig. 5, the nine biological attributes of the four k and r fish groups showed that the most attributes consistently increased or decreased along group 1 to group 4, or clearly differed between group 1, 2 and group 3, 4. This indicates that four fish groups well represent different life history strategy in the k-r spectrum.
Figure 4. Dendrogram (a) and NMDS (b) results of Tonle Sap ecosystem fish species group classification based on nine biological attributes. Note: stress value < 0.05 gives an excellent representation, < 0.1 corresponds to good ordination, 0.2-0.3 still gives potentially useful 2-dimensional picture, between 0.2-0.3 should be treated as doubtful if the sample size less than 50, and stress > 0.3 indicates that the points in the picture are arbitrarily placed (Clark and Warwick 1994). Three species are heterogeneous and not included in k and r fish groups.

Figure 5. k and r fish species groups of Tonle Sap ecosystem and their nine biological attributes. Note: the k and r fish species groups were in order from the left to the right. The resilience and main food attributes are the category data type.
The numbers of fish species (154) of bag net fishery were many more than lot (70) and/or middle scale (45) fisheries because of different species record systems “before” and “after” the year 2001 (“before”: only 40 major species were taxonomically identified, and “after”: all species were taxonomically identified). The fish species compositions by $k$ and $r$ species were similar in three environments (e.g. the TS River, open lake and floodplain), the largest (45-48%) was group 3, the groups 2 and 3 were next largest (16-28% for each group) and the least (4-5%) was group 1. However, the catches of $k$ and $r$ fish groups differed at three environments (Fig.6): in the TS River, the group 4 dominantly contributed between 40 and 66% of annual catch, the next contributor (20-40%) was group 3, while group 1 or 2 contributed between 5 to 10% each; In the open lake, the contributions of groups 2, 3 and 4 were similar 30-33%, 26-28% of group 3 and 24-31% of group 4; In the floodplain, the largest contributor 43-54% was group 2, the next largest 19-40% was group 3 and similarity of group 1 and 4 contributed about 10% each. At the family level, the Cyprinidae family contributed 77%, 56% and 31% to catches in the TS River, open lake and floodplain environments respectively and the Channidae family contributed 29% to the catch in floodplain, 9% to the catch in open lake and 1% to the catch in the TS River during period 1995-1999. The $r$ species of groups 3 and 4 of bag net fishery in the TS River was gradually decreasing during 1995-2002.

The strong multi-correlation (40.15% on component 1 and 34.4% on component 2) among 24 dominant species quantitatively contributing about 80% to the annual catch in the TS River and floodplain during 1995-1999 was shown in Fig.7a. The $k$ and $r$ species groups were distinctly projected into two different areas on PCA, almost $r$ species of groups 3 and 4 were distributed in top-left half circle, while the $k$ species of groups 1 and 2 were distributed in the bottom-right half circle. Note that the correlation between any two species was related to the cosine of the angle between the vector joining the origin and the species positions and the distance between the species locations in the Euclidean space (McGarigal et al 2000). In the Euclidean space, the group of Pangasius hypophthalmus sp, Micronema spp and Channa micropeltes was negatively correlated with group of Cyclocheilichthys apogon spp, Osteochilus melanopleurus, Puntioplites procozysron and Trichogaster microlepis on component 2, and group of Channa marulius, Hemibagrus nemurus was negatively correlated with group with group of Hampala dispar, Botia spp, Dangila spp and Paralaubuca typus on component 1. The Pearson correlation test applied for each pair species among these 24 dominant species showed that there were 20 significant correlations among these species. Of which, 11 negative correlations (the solid arrows in Fig.7b) were formed among species between $k$ species (groups 1 and 2) and $r$ species (groups 3 and 4) with exception the correlations between Channa micropeltes and Channa marulius and between Paralaubuca typus and Setipinna melanochir. While the positive correlations were formed among species within and between group 3 and/or group 4 (the dotted arrows in Fig.7b). The trophic structure and energy flow of fish community in the TS ecosystem was illustrated based on these correlations (Fig 7b). Pangasius hypophthalmus/sp, Channa marulius, Hemibagrus nemurus, Micronema spp and Channa micropeltes at the higher trophic level were the key predators driving the energy flow, while Dangila spp, Henicorhynchus spp, Biota spp, Cyclocheilichthys apogon/spp, Hampala disparr, Puntioplites procozysron, Osteochilus melanopleurus and Trichogaster microlepis at the lower trophic level were the preys contributing to the
energy flow among fish community in the TS ecosystem. In general, the ratios between the preys and predators, which based on the annual catch proportion, were low with exception of the ratio (21:1) between *Henicorhynchus* spp and *Hemibagrus nemurus* (Fig. 7b).

**Figure 7.** The multi-relationships of 24 dominant species of lot and bag net fisheries during 1995-1999 on components 1 & 2.

**Projection of 24 dominant species annual catches of lot and bag net fisheries during 1995-1999 on components 1 & 2.**

(b) Species correlation and tentative trophic model of fish community in the TS ecosystem based on

**Figure 7.** The multi-relationships of 24 dominant species of lot and bag net fisheries in floodplain and the TS River environments respectively (a) and the initial trophic model of fish community in the TS ecosystem (b)

**Tonle Sap ecosystem hydroecological index development.**

The annual water level patterns in the three phases, namely the drought, flood and receding durations at the Kampong Luong station were similar as shown in Fig. 8a, b and c. However, the timing, duration and water level in each year were different. For example, the shortest drought duration and the highest water level were in 2000; the longest drought duration and the shallowest water level were in 1998; the earliest and the latest flood timing were in 2000 and 1998 respectively; and the longest and the shortest receding duration were in 2002 and 1998 respectively. Based on the methods of hydrological parameter identification discussed in the methodology section above, eight potential hydroecological parameters were identified. Figure 9 presented the two-dimensional ordination illustrating the major patterns of the high inter-correlation (61.86% on component 1 and 18.14% on component 2) among eight potential hydro-ecological parameters and bag net fish catches during eight years. Similar explanation for the intercorrelation among species above, the correlation between any two hydroecological parameters was related to the cosine of the angle between the vectors joining the origin and the parameter positions and distance between parameter locations in Euclidean space. Therefore, on component 1, five parameters, namely average drought inundated dear, maximum flood inundated area, flood and receding durations were positive correlations with bag net fish catches, and inversely flood timing and drought duration were negative correlations with bag net fish catches. Having high correlation coefficients greater than +/−0.75 on component 1 of PCA (Fig. 9) as the criteria discussed in the methodology above, five parameters including drought duration, average drought inundated area, flood timing, maximum flood inundated area, and receding duration were alternatively selected to constitute the HEI. These parameters values were shown in Table 1. Although the water level parameter was high correlation on component 1, it was not selected to constitute the HEI, because the selection priority was given to maximum inundated (see the criteria for parameter selection in the methodology section above). Flood duration and receding slope were excluded from the HEI development because they had low correlation coefficients (+0.62 and -0.13) on component 1 (Fig. 9). The highest positive correlation coefficient in the multi-correlation between and within hydroecological parameters and bag net fish catch was maximum inundated area (+0.96), the next highest negative correlation coefficients were flood timing (-0.93) and drought duration (-0.91).

The results of parameter threshold identification, scoring and narration were shown in Table 1. Because having positive correlations with fish catches on component 1, three grouped values identified by the lower and upper thresholds of each parameter of average drought inundated area, maximum flooded area and receding duration were assigned scores of 1, 3 and 5 in accordance with the
increase of these parameters, and narrated as poor, fair and good conditions respectively. Inversely, having negative correlations with fish catches on component 1, the grouped values of each parameter of drought duration and flood timing were assigned scores of 5, 3 and 1 in accordance with the increase in those parameter values and narrated as good, fair and poor conditions respectively. The yearly HEI and parameter scores (in the parentheses) were shown in Table 1. The distribution of years in the multi-correlation among hydrological parameters and fish catch was shown Fig.9. The maximum HEI of 5 was in year 2000, which was in the same direction of total bag net fish catch (Fig.9) and had the largest drought and flood inundated areas, the longest receding duration and the shortest drought duration and the earliest flood timing (Table 1). In contrast, the minimum HEI of 1 was in year 1998 that was in opposite direction with total bag net fish catch (Fig.9) and had the smallest drought and flood inundated areas, the shortest receding duration, the longest drought duration and the latest flood timing (Table 1). The gradient change in the HEI from the highest in 2000 to the lowest in 1998 was shown in Fig.9. Importantly, there was a significant correlation between total bag net fish catch and HEI \((r = +0.644, P<0.05)\), the change in the HEI and total bag net fish catch in relative years was shown in Fig.10. In Table 2, the correlations between HEI and the hydrological parameters in year \(y\) and bag net fish catches in year \(y\) and \(y+1\) indicated that the hydrological condition influenced fish production cross the years, in particular in year \(y+1\). Six hydrological parameters in year \(y\) were significantly correlated with total fish catch or the \(k\) and \(r\) fish group catches in year \(y+1\). Of four parameters that were significantly correlated with fish group 2 in year \(y\), the highest negative correlation was flood timing \((-0.875, P<0.01)\) and the highest positive correlation was drought inundated area \((+0.806, P<0.05)\) with group 3 in year \(y+1\). The flood duration was significantly correlated with total catch in year \(y+1\) and fish group 2 in year \(y+2\). There were negative correlations between receding duration and fish group 1 in year \(y\) and fish group 4 in year \(y+2\) and between maximum inundated area and fish group 4 in year \(y+2\). There was no significant correlation between receding slope and fish catch.

Table 1. Five selected hydroecological parameters values, scores and threshold values

<table>
<thead>
<tr>
<th>Parameter values and index scores by year</th>
<th>Parameter threshold values</th>
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<tr>
<td>Year</td>
<td>Parameter</td>
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<td>-----</td>
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<tr>
<td></td>
<td>Drought duration (day)</td>
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<td></td>
<td>Avg. drought inundated area (km²)</td>
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<tr>
<td></td>
<td>Max. flood inundated area (km²)</td>
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<td></td>
<td>Receding duration (day)</td>
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<td></td>
<td>Flood timing (day)</td>
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<td></td>
<td>Total catch (t)</td>
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<td></td>
<td>Total score</td>
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<td></td>
<td>HEI</td>
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<td>Rating narration</td>
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Note: Exp.Res = Expected responses to fish catches, \(P\) = Positive, \(N\) = Negative. \(ai\) and \(bi\) are parameter thresholds. The numbers in the parentheses indicate the parameter scores in relative years. The annual total catches of four fish biological groups in the Table 1 is approximately 95% of the annual total Dai catch in the Table 2, because the rest (5%) of catches is the proportions of the very small species, which are not taxonomically identified in fish catch statistic.
Figure 8. Hydrograph at the Kampong Luong station: water level and drought (a), flood (b), and receding (c) phases.

Table 2. Correlation between the hydrological parameters and HEI in the year y and fish catches in the year y, y+1 and y+2.

<table>
<thead>
<tr>
<th>Year y</th>
<th>Hydrological parameters and HEI in year y</th>
<th>Dai fish catch in year y, y+1 and y+2</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Drought duration</td>
<td>Drought inundated area</td>
</tr>
<tr>
<td>Year y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>-0.523*</td>
<td>0.368</td>
</tr>
<tr>
<td>Group 1</td>
<td>-0.072</td>
<td>0.190</td>
</tr>
<tr>
<td>Year y+1</td>
<td>0.023</td>
<td>0.126</td>
</tr>
<tr>
<td>Group 2</td>
<td>-0.795*</td>
<td>0.806*</td>
</tr>
<tr>
<td>Group 3</td>
<td>-0.305</td>
<td>0.318</td>
</tr>
<tr>
<td>Year y+2</td>
<td>-0.166</td>
<td>0.195</td>
</tr>
<tr>
<td>Group 4</td>
<td>0.410</td>
<td>-0.192</td>
</tr>
</tbody>
</table>

Note: (*) and (**) indicate for significant correlation $P<0.05$ and $P<0.01$ respectively.

Figure 9. Intercorrelation among hydrological parameters and total bag net fish catches and distribution pattern of years on PCA.

DISCUSSIONS

Nine representative biological attributes of the TS ecosystem fish species obtained from the FishBase database were useful to classify all fish species found from fish catches into four $k$ and $r$ strategists groups by using clustering and NMDS analyses (Fig.4).

Compared to the previous researches, the $k$ and $r$ species groups that classified by combining nine biological attributes are well representing the life history groups of the TS ecosystem fish community and they would differ sensitive responses to different conditions of environment. In the previous researches, only some dominant species were taken into account for analysis based on the attribute of “black”, “grey”, “white” and “opportunities”, these were categorized mainly based on fish migration pattern (Lieng et al 1995, Van Zalinge and Thouk 1999, Baran and Cai 2001 and Van Zalinge et al 2003). Another research of Lim et al (1999), the distribution of fish orders and families were illustrated quantitatively based on bag net and lot fisheries data. However, the species life history is very diverse within a fish order and/or family. The $k$ and $r$ species compositions are similar in both the lake and river, and the $r$ species of group 3 was dominant in both the systems. The dominances in catches of Cyprinidae family, the more longitudinal migrants, demersal and pelagic species, in three environments especially in the TS River and open lake indicates that the TS ecosystem fish production is very much dependent on migratory fish species from outside and the importance of water column habitat type to fish species of Cyprinidae family. The dominance of Channidae family, the more lateral migrants and benthopelagic species in floodplain environment with dense vegetation.
indicates the importance of vegetation habitat in the floodplain to species in *Channidae* family. At the *k* and *r* species groups, the dominant contributions of groups 3 and 4 to the annual bag net catches in the TS River, of groups 2, 3 and 4 to the annual catches of middle scale fishery in open lake and of group 2 and 3 to the annual catches of lot fishery in the floodplain indicate the important functions of the TS Lake and its floodplain as the sheltering, spawning and feeding grounds (Lambert 2001) for more *k* species in particular, while the TS River functions as the transition habitat (Lim et al 1999) for *r* species in particular.

The multi-relationship among 24 dominant species contributing to fish catches during 1995-1999 is well projected on the two-dimensional components of PCA (Fig. 7a). The far distances from species location to the origin and the large cosine angle between each pair-wise of *k* and *r* species indicate the strong biological relationships among fish species in the TS ecosystem. The negative correlations of some species on component 1 and 2 may possibly indicate the TS ecosystem fish community structure from the viewpoint of predator-prey, *k* and *r* species, relationships. While the negative correlations between two species of *Channidae* and between *Paralaubuca typus* and *Setipinnia melanochir* (Fig. 7a and b) may possibly indicate the food and/or habitat competition relationships between these fish species. According to Junk et al (1989), in the flood pulsing ecosystem of the river-floodplain system, many small *r* fish species were preyed upon by efficient *k* fish species predators. However, in the TS ecosystem, the low ratios between *r* and *k* species for each pair-wise comparison (Fig 7b) may possibly indicate the function of crustacean, zooplankton, vegetation and/or detritus and others as the additional food sources for *k* species in the higher trophic level. This also is hypothesized that there is an insufficient energy flow (i.e. lack of the supplying food source at the low trophic level to the higher trophic level) of the TS ecosystem fish community food chain because the decrease of *r* species (groups 3 and 4) in bag net fish catches during 1995-2002, which is possibly caused by the influence of a prolonged “fishing down” practice (e.g., nowadays if the natural stock of larger fishes is small, the fishing gear with smaller mesh size is used to catch smaller fish) in the TS ecosystem. Bag net at one time is an example of “fishing down” practice in the TS ecosystem. However, to better understand biological process and interaction within fish community and between fish community and other aquatic flora and fauna, the studies of gut content analysis, feeding habits and habitat preferable are necessarily. The decrease of the *r* species may also be influenced by other environmental parameters relative to water quality, habitat disturbance and catchment land use. In order, to better understand the change in the TS ecosystem fish catch/production and particularly the decrease in the *r* fish species, the further studies on the TS ecosystem water quality, catchment land use and other fishing activities in the TS Lake are necessary along with the use of the HEI.

The variations in the hydrological parameters and their relationships with fish catch are clearly projected on PCA (Fig. 9). The large angles and far distances from the location of each hydrological parameter to bag net fish catch on the Euclidean space (Fig. 9) significantly support the parameter definition and determination that proposed in the method section as well as the hypotheses given by Baran and Cain (2001), Baran et al (2003) and Welcomme and Halls (2003) that mentioned in the introduction section. The highest positive and negative correlation coefficients of maximum inundated area, flood timing and drought duration on factor 1 suggest that these parameters are important to influence the increase or decrease of fish production respectively and possibly provide an acceptable explanation for the high fish catch (14,974 tons) in 2000 and the extremely low fish catch (8,894 tons) in 1998. Van Zaling et al (2003) found out that in the TS ecosystem the water level of year *y* was significantly correlated with bag net fish catch in the same year, but not in year *y*+1 and *y*+2. However, in this study, the strong correlation between the five selected parameters and HEI in year *y* and the fish catches of group 2 and 3 in years *y*+1 (Table 2) indicate that the impacts of hydrological condition interact across years and vary by the fish biological groups. Particularly, the flood timing and drought duration in year *y* are factors that limit effective reproduction and survival of fish group 2, and subsequently these influences are negative impact on this fish group production in year *y*+1. While, the inundated area in year *y* is factor that provides more refuge to escape the predators and reduce the space-competition caused by the high density population attribute, especially for smaller fishes of group 3, and subsequently supports fish productions of group 3 in year *y*+1. However, this assumption should be more studied together with fish community structure in the view of points of habitat and food competition. The significant correlations between flood duration and fish production in year+1 and fish group 2 in *y*+2 indicate that this parameter is potential impact on fish production in the later years rather than in the entire measurement year. The receding slope was insufficient in response to the fish catch; this perhaps is due to the river-floodplain pulsing hydrological regime in the TS ecosystem. Having highest correlation coefficients with bag net fish catches on PCA in the entire measurement year and interaction cross the years, the flood timing and inundated area are very important factors that influence the fish production in the TS ecosystem.

The correlated interaction cross the years between HEI and bag net fish catches in the TS ecosystem indicates that the fish catch is sensitive
response to the HEI. Therefore, the HEI is a potential hydroecological monitoring tool that can be used to assess the relationship between hydrological conditions and fish production and support hydropolicy scenarios and decisions. The threshold values of a given hydrological parameter (Table 1) are potentially used as the criteria to assess the impact of that parameter, while the relative scores are used to calculate the HEI. In the HEI development based on benthic biota for a New Zealand stream system, the flood frequency is the most sensitive to Chl-a, species richness, number of species and the diversity index (Clause and Biggs 1997), instead of inundated area and flood timing like in the TS ecosystem. This difference is perhaps due to the different responses of the benthic biota and fish production and different characteristics of the flood pulse of the river-floodplain system in the TS ecosystem and stream flow in the New Zealand stream system. However, to better understand the influences of other hydrological parameters and to improve the HEI for the TS ecosystem, the flow frequency as applied to the HEI for the New Zealand stream and the flow rate that introduced by Olden and Poff (2003) and the monthly variation of hydrological parameters applied by Richter et al (1996) should be considerably taken into account. The negative correlations between receding duration and maximum inundated area in year y and fish group 1 and fish group 4 in year y and y+2 respectively (Table 2) may be due to natural cause of the interdependent complexity in ecological process, wherein some species become dominant in the suitable environment and possibly drive the other species population by preying upon and food and/or habitat competing. However, to support these conclusion and assumption, it is important to further study the TS ecosystem fish community structure cross the years.

ACKNOWLEDGEMENT

We would like to express our gratitude to the MRC organization, Cambodia Department of Fisheries, the WUP-FIN Project, COE Program of the University of Yamanashi and Sunada CREST Project of the Japan Science and Technology Agency (JST), FishBase organization and local people living around the TS ecosystem for their guidance and support.

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