Application of holistic and analytical models for the management of tilapia fisheries in reservoirs

Aplicación de modelos holísticos y analíticos para el manejo de pesquerías de tilapia en embalses

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ABSTRACT

Reservoir fisheries are widely disseminated around the world. Their scarcely regulated exploitation justifies the use of models to achieve a precautory management. As an example of the utility of holistic and analytic models to analyse reservoir fisheries, it is presented the specific case of the tilapia fishery in the Infiernillo reservoir in Mexico. Schaefer and Fox models permitted an understanding of the history of fishery, while the current state of the stock was examined by applying Beverton & Holt, Cohort Analysis of Jones and Thompson & Bell models. Recommendations for the management of the fishery were based on simulation processes. Applying those models, it was found that the tilapia fishery surpassed its sustainable yield in 1988. In 1993 the fishery reached a new state of equilibrium. At present the fishery is in a deteriorated state. The fishing impact is on organisms in the reproductive stage. The current maximum sustainable yield is 8,698 tons. Simulation processes show that an increase in the mesh of the gill nets up to 10 cm and a decrease in the fishery effort down to 20,000 gill nets and 3,100 fishermen could help the fishery to recuperate. Holistic and analytical models are useful to evaluate reservoir fisheries.

Key words: Reservoir fisheries, fishery management, tilapia management, tilapia fisheries, holistic and analytical models.

RESUMEN

Las pesquerías de embales están ampliamente diseminadas alrededor del mundo. La escasa regulación en su explotación justifica el uso de modelos para lograr su manejo precautorio. Como un ejemplo de la utilidad de los modelos holísticos y analíticos para analizar pesquerías en embalses, se presenta el caso específico de la pesquería de tilapia en la presa Infiernillo, México. La aplicación de los modelos de Schaefer y Fox permitieron entender la situación de la pesquería en el pasado, mientras que el estado actual del stock fue analizado aplicando los modelos de Beverton & Holt, Análisis de Cohortes de Jones y Thompson & Bell. A través de procesos de simulación se establecieron propuestas para el manejo de la pesquería. La aplicación de estos modelos permitió detectar que la pesquería de tilapia en Infiernillo sobrepasó su máximo rendimiento sostenible en 1988 y en 1993 alcanzó un nuevo estado de equilibrio. Actualmente la pesquería se encuentra en un estado deteriorado y registra un rendimiento máximo sostenible de 8 698 toneladas. La incidencia de la pesca es sobre organismos en estado reproductivo. El proceso de simulación mostró que un incremento en la abertura de malla de las redes agalleras con que es capturada la tilapia a 10 cm y un decremento en el esfuerzo pesquero por debajo de 20 000 redes agalleras y 3 100 pescadores, podría contribuir a la recuperación de la pesquería. Los modelos holísticos y analíticos son herramientas útiles en la evaluación de pesquerías en embalses.

Palabras clave: Reservoir fisheries, fishery management, tilapia management, tilapia fisheries, holistic and analytical models.

INTRODUCTION

Tilapias fishery supports some of the main reservoir fisheries established around the world (Petr, 1987; Welcomme, 1988; Crul & Roest, 1995; Ochumba *et al.*, 1992; Remane, 1997). Despite the enormous benefits that tilapia fisheries have provided, particularly to rural communities, producing nutritive food at low cost, generating employment and producing socio-economic changes that have contributed to community development (Sugunan, 1995), few efforts have been made to manage their exploitation, based on scientific models.

In the past, tilapia characteristics such as its fast growth, multiple spawning, high resistance to disease, consumption of a variety of foods and its adaptation to freshwater and marine environments (Keenleyside, 1991), encouraged its dissemination in several reservoirs without any desirable control. The consequence of this lack of management is that, at present, the tilapia is dispersing around the world and in some cases has displaced native fish in the competition for breeding space and feeding (Rosas, 1976; Welcomme, 1988; Sugunan, 1995).

Tilapia populations in the majority of reservoirs were introduced from Africa in stocks of few ancestors and disseminated from these to other reservoirs (Welcomme, 1988). Consequently, the genetic pool is probably much deteriorated.

Currently, tilapia fisheries in Mauritania, Indonesia, Madagascar, India, Egypt, Africa and Mexico, are notably depleted. The consequences of overexploitation and genetics include a reduction in mean capture size, an early sexual maturation, deformities in their morphology, endogamy, etc. (Petr, 1987; Morales, 1991; Ochumba *et al.*, 1992; Crul & Roest, 1995; Sugunan, 1995; Remane 1997). Therefore a careful management with consideration for ecological, genetic and fishery factors is required.

Holistic models are satisfactorily used to evaluate marine and freshwater fisheries when catch and effort data are available, which is not very common. These models analyze the historical tendency of the fishery. While analytical models based on the age or length structure of the population, show the present status of the stock and are be able to forecast the future status when one fishery is exploited under the same pattern. So these models are a useful tool in fisheries management.

As an example of the utility of holistic and analytic models in supporting the management of reservoir fisheries, here present their application in one important reservoir fishery in Mexico.

MATERIALS AND METHODS

The Infiernillo Dam is an important Mexican reservoir of 34 600 ha, 35 m in mean depth, 70 m in maximum depth and 120 km length, located at 18o 16′ 30′′ N and 101o 53′ 40′′ W, between Michoacan and Guerrero states (Juárez, 1995). The main tilapia fishery of Mexico is established here and the most abundant species caught is *Oreochromis aureus* (Steindachner). Current fishing activity is carried out by 1 861 fishermen on 669 fibre glass boats with outboard motors, 560 wooden boats paddled and 18 435 gill nets of 35 m length, 3 m wide, 8.3 and 10.8 cm mesh size.

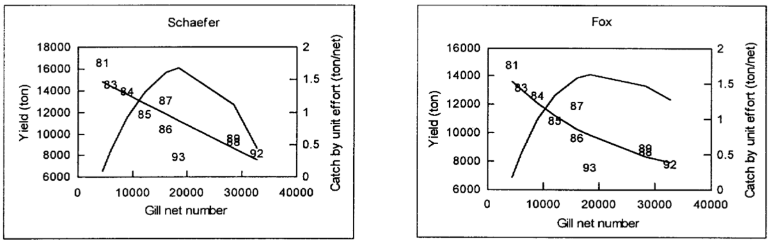
Thirteen years of data on the tilapia catch and fishing effort in Infiernillo reservoir were obtained from the Regional Fishing Office in Nueva Italia, Michoacan, Mexico.

These data were used to analyse the historical trends of the fishery applying the holistic models of Schaefer (1954) and Fox (1970) according to Sparre and Venema (1995). A calculus sheet was used to carry out a lineal adjustment between catch per unit effort (Y/f) and the effort (f) in the first model and between natural logarithm of the catch per unit effort (ln Y/f) and the effort (f) in the second. Two fishing effort units were considered in the analysis: number of fishermen and number of gill nets. The optimum fishing effort (F) and the maximum sustainable yield (MSY) which assures the stock's long term sustainability were obtained from those relationships.

The daily tilapia catch during one year was obtained from the purchases' registry, in thirteen landing places. In four of them, which represent 70 % of the captures, samples of fish length and weight were obtained in order to determine the length and weight structure of the population. Those structures were extrapolated to the other landing places according to Gulland (1966) and Sparre and Venema (1995) in order to have a representative length distribution of the annual total catch. The economic value of the catch was recorded too.

To analyse the present state of the stock, analytical models such as Beverton and Holt (1957), Cohort Analysis of Jones (1984) and Thompson and Bell (1934), were applied, based on length structure of the population.

The input data on tilapia growth, mortality and recruitment parameters used in those models were: L_∞ = 478 mm, K= 0.46 annual, t_0= -0.055 annual, W_∞ = 3 446 g, Z = 3.5, M = 1.4, F = 2.1, Lr = 93 mm, estimated by Jiménez (in press) and the gill net selectivity parameters: Lma = 176 mm, Lmb = 231 mm, Lc = 176 mm, estimated by Jiménez *et al.* (2001). These parameters were estimated using opercular and scale lectures and length frequency analysis, considering tilapias ranging



$Y/f = 1.65 - 0.000043\ f$

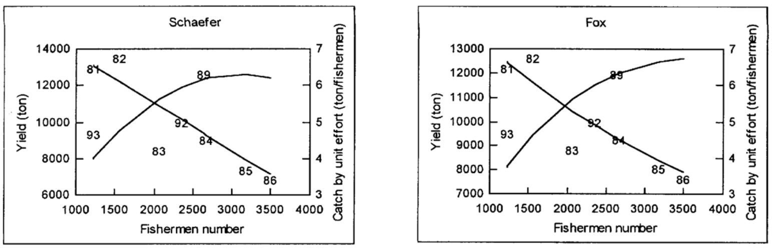
MSY = 16,133 tons

F_{MSY} = 19 474 nets

$Y/f = 1.89\ e^{-0.000049\ f}$

MSY = 14,169 tons

F_{MSY}.= 20 226 nets



$Y/f = 8.15 - 0.00132\ f$

MSY = 12,627 tons

F_{MSY} = 3 096 fishermen

$Y/f = 9.2\ e^{-0.00027f}$

MSY = 12,633 tons

F_{MSY} = 3 729 fishermen

Figure 1. Optimum yield and fishing effort (MSY, F_{MSY}) for tilapia fishery in the Infiernillo reservoir, based on Schaefer and Fox models, considering thirteen years of data of catch per unit effort (Y/f), where effort unit was nets and fishermen separately (f).

from 40 to 335 mm standard length and Saila non linear growth model (Saila *et al.*, 1988).

The yield per recruit model of Beverton and Holt (1957), in conjunction with the FISAT package, made it possible to develop yield isopleths relative to recruitment. Their analysis throughout the simulation process varying the length at first capture (Lc) and the fishing mortality rate (F), together with the gill net selectivity analysis made by Jiménez (1999) and Jiménez *et al.* (2001), suggested the best mesh opening of the gill nets for catching tilapias. This model also provided estimates of the maximum sustainable yield per recruit (MSY/R) and the optimum fishing mortality rate ($F_{MSY/R}$).

To analyze the fishing effect on a particular annual class of the stock, the length structure of the population derived from the daily catch samples during one year was used to apply a Cohort Analysis of Jones (1984). The weight in the total catch was transformed to number of individuals per length group, using elevation factors considering the length distribution frequency, according to Sparre and Venema (1995). To establish the terminal value of F that permitted starting the cohort analysis, an iterative procedure was used with 0.5 as initial value. The cohort analysis was carried out changing

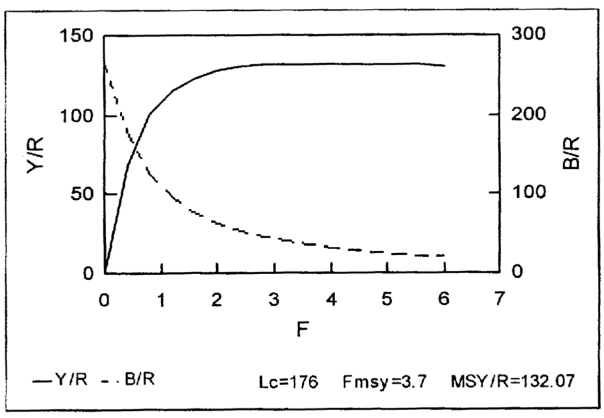


Figure 2.Yield and biomass per recruit (Y/R, B/R) for *Oreochromis aureus* in function of the fishing mortality rate (F). Maximum sustainable yield per recruit (MSY/R), fishing effort optimum (Fmsy), first catch length (Lc).

Table 1. Results of the simulation process based on the Thompson & Bell model, using different fishing scenarios. The maximum sustainable yield (MSY), maximum sustainable economic yield (MSE), the corresponding biomass (B_{MSY}, B_{MSE}) and their optimum fishing mortality rate (F) are presented.

	F	Yield (tons)	Mean Biomass (tons)	Value ($ * 10^3)
	0.0	0,000.00	18,945.58	0000.00
	0.4	3,122.57	13,933.96	5,546.49
	0.8	5,183.54	10,421.43	9,008.68
	1.2	6,533.55	7,947.93	11,122.27
	1.6	7,407.86	6,197.27	12,369.86
1	2.0	7,964.52	4,951.26	13,067.32
	2.4	8,309.83	4,058.77	13,420.56
	2.8	8,515.24	3,414.80	13,563.03
	3.2	8,628.75	2,946.13	13,584.59
	3.6	8,682.53	2,601.57	13,527.41
	4.0	8,698.09	2,345.22	13,437.83
	4.4	8,689.67	2,151.85	13,332.50
	4.8	8,666.78	2,003.68	13,223.66
	5.2	8,635.57	1,888.13	13,118.16
	5.6	8,600.05	1,796.28	13,019.44
	6.0	8,562.76	1,721.80	12,928.93
		MSY = 8,698.09	F =	4
		B_{MSY}= 2,307.42		
		MSE =13,584.60	F =	3
		B_{MSE} = 3,082.72		

1 Scenario in 1993

the F value at random every time. When the difference between the observed catch per unit effort ($Y/_{fobs}$.) and the estimated catch per unit effort (Y/f_{est}.) was zero, the optimum value for $F_{terminal}$ was established and the cohort analysis was finished. The $Y/_{fobs}$ corresponded to the purchases' register and the $Y/_{fest}$. was derived from the relationship between mean mortality rate, mean biomass and effort. This analysis was carried out on an iterative calculus sheet designed on Q-Proo package, following the mathematics functions presented in Jones (1984).

As the total catch in one year with a daily periodicity was available, this model provided an estimation of the stock size (N), which should have existed to produce such a catch. The mean annual biomass (Bm) of all cohorts, the yield (Y) and the number of individuals that died due to fishing and natural causes were estimated too. The fishing pattern (F) at the Infiernillo was established by the fishing mortality per length group (F(L)).

Those results related to the tilapia economic value were incorporated to the Thompson and Bell (1934) model implemented with FISAT package, to forecast the future effects of several fishing effort levels on the stock biomass, yield and economic value. Several fishing scenarios were simulated increasing fishing mortality from 20 to 200 % and diminishing it from 20 to 80 %, in order to establish recommendations for fishery management. The maximum sustainable economic yield (MSE) was also estimated according with Sparre and Venema (1995).

RESULTS

Infiernillo reservoir was flooded in 1964. The tilapia fishery started in 1970. Since then on the production had fluctuated between 3 000 and 19 000 t annually, according to historical data. The highest production was reached in 1987 when the reservoir occupied the first place in Latin America (Júarez, 1995). After that, the tendency was to decrease until it dropped to 4 770 t in 1999, which represents only 25 % of the highest level registered.

The Schaefer and Fox models applied to these data provided the yield curves shown in figure 1. The MSY and FMSY levels for each fishing effort unit are also indicated. According to both models, the optimum effort level was exceeded in 1988, when 28 422 nets were operating. One year before, when 16 150 nets were operating, the fishery reached the highest catch (18 953 t) in its history. Maybe this situation encouraged the entrance of 76 % more nets for the next year. Consequently, the production dropped to 15 076 tons. The insufficient control of tilapia exploitation, led to a continuous increase of nets, until it reached 32 750 nets in 1992.

The 3 486 registered fishermen in 1986 dropped to 2 343 in 1992 and 1 861 for 1999. Probably this reflects the migration of fishermen to other activities, caused by the low income from fishing activity. This drop in the fishing effort is only apparent, because in the last few years, the use of nets has risen to an average of fifteen per fisherman, whereas in 1987 it was only five per fisherman. Therefore, the fishing effort has actually increased, with a consequent decrease in the catch.

After exceeding its maximum sustainable levels, the fishery reached a new state of equilibrium in 1993. In this year the yield per recruit was 127.7 g/recruit and the fishing mortality rate was 2 (Figure 2). This means that the fishery was near its new point of equilibrium (MSY/R), established at 132 g/recruit and the $F_{0.1}$[1] level of 1.2, had been exceeded.

Table 2. Cohort Analysis for *Oreochromis aureus* in the Infiernillo reservoir. Population size (N); exploitation coefficient F(L)/Z(L), fishing mortality rate F(L) and total mortality rate Z(L) per length group; mean number of individuals (Nm); population removed by natural death (Nd).

Length group	Capture (individuals)	N (individuals)	F(L)/Z(L)	F(L)	Z(L)	Nm (individuals)	Weight (g)	Mean annual Biomass	Yield (tons)	Nd (individuals)
130 - 140	797,726	75,900,275	0.11	0.17	1.65	4,561,059	91.2	416,032.210	72.764	6,750,367
140 - 150	2,326,245	68,352,181	0.27	0.56	2.04	4,173,630	112.0	467,351.355	260.486	6,176,973
150 - 160	5,681,577	59,848,964	0.51	1.56	3.04	3,642,353	135.6	493,898.070	770.414	5,390,682
160 - 170	11,773,100	48,776,705	0.74	4.18	5.66	2,816,894	162.3	457,038.558	1,910.175	4,169,004
170 - 180	9,823,324	32,834,601	0.78	5.20	6.68	1,889,020	192.1	362,876.645	1,887.040	2,795,749
180 - 190	5,999,338	20,215,529	0.77	4.99	6.47	1,202,091	225.3	270,846.810	1,351.729	1,779,095
190 - 200	2,257,433	12,437,096	0.65	2.76	4.24	817,504	262.1	214,236.096	591.585	1,209,906
200 - 210	1,125,021	8,969,757	0.55	1.79	3.27	629,267	302.5	190,358.189	340.328	931,314
210 - 220	640,109	6,913,422	0.46	1.25	2.73	511,363	346.8	177,350.035	222.001	756,818
220 - 230	409,315	5,516,495	0.39	0.96	2.44	427,329	395.2	168,860.950	161.743	632,446
230 - 240	272,890	4,474,733	0.34	0.75	2.23	362,486	447.7	162,277.947	122.167	536,479
240 - 250	179,373	3,665,364	0.28	0.58	2.06	310,759	504.6	156,795.328	90.504	459,923
250 - 260	142,383	3,026,069	0.26	0.53	2.01	267,492	565.9	151,385.406	80.581	395,888
260 - 270	56,899	2,487,798	0.14	0.24	1.72	232,400	632.0	146,877.404	35.960	343,952
270 - 280	45,215	2,086,947	0.13	0.22	1.70	203,926	702.9	143,337.689	1.781	301,810
280 - 290	36,486	1,739,922	0.12	0,20	1.68	178,158	778.8	138,743.710	28.414	263,674
290 - 300	10,598	1,439,762	0.01	0.01	1.49					
		358,685,618				22,225,731		4,118,266.402	7,957.672	
		$Y/f_{obs.}$=17.98		$F_{terminal}$ =0.011			$Y/f_{esp.}$=17.98			

In absolute terms, the new maximum sustainable yield was estimated at 8 698 tons, and the maximum economic yield at $ 13,584,600[2] (1 234 964 USD) (Table 1). In 1993, the yield was 7 964 t and the economic value $ 13,067,320 (1 187 938 USD). This confirms that in that year, the new state of equilibrium was reached.

The simulation process results show a scenario in which when duplicating or increasing the fishing mortality rate 50 %, an increment in the yield and the economic benefit could be reached (Table 1), but it is a dangerous strategy because it represents only an increase over 8% and 4%, respectively, versus the risk of exceeding once again the new state of equilibrium and the abrupt decrease in the catch per unit effort. Then the better strategy is to reduce the fishing effort.

The Cohort Analysis provided a similar yield of 7 957 t and it estimated that a population of around 358 million individuals should have existed to provide this catch (Table 2). The F estimation by length group showed heavy fishing pressure on individuals from 150 to 200 mm standard length, caught mainly with gillnets of 8.3 cm of mesh size (Figure 3). The adult population is scarcely removed by fishing.

In the simulation process it was evident that a better yield per recruit had been reached when the length of the first catch was established at 210 mm and the fishing mortality rate maintained between 3.2 and 4 (Figure 4).

DISCUSSION

After being an excellent option in food production at low cost, the tilapia fishery is now insufficient to satisfy the demand due to the continuous drop in the captures. This situation is reflected in the yield of 0.17 kg/m^2/year for the Infiernillo reservoir and the yield from 0.25 to 0.65 kg/m^2/year

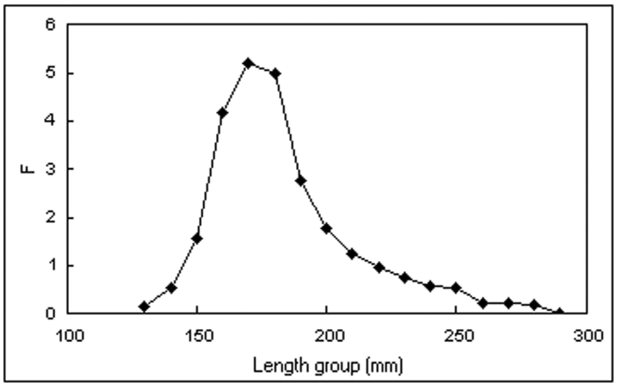


Figure 3. Fishing pattern at Infiernillo showed heavy fishing pressure on juveniles of tilapia. Fishing mortality rate (F).

reported by Jumbe (1997) for African dams and reservoirs, in spite of their great potential.

In thirty years of existence, the tilapia fishery in Infiernillo has experienced inefficient management that in one occasion has led to surpass its maximum sustainable yield and can be in risk to surpass the new state of equilibrium as Schaefer, Fox and Thompson & Bell models showed.

Since this fishery started, regulation measures consisted of sporadic closed season and the use of gill nets of 8.3 cm mesh size, which catch tilapias when they have not yet spawned. The first maturity length for *O. aureus* is 170 mm, according to Jiménez (1999) and the fishing pressure is mainly on individuals from 150 to 200 mm standard length according to the Cohort Analysis of Jones. These data showed the inadequacy of the current fishing process.

In spite of the inadequate exploitation process, this tilapia population still exists. Maybe its reproductive success has been able to counteract the fishing extraction, but with more and more difficulty, as the continuous decrease of the catch demonstrates.

Individuals longer than 210 mm are caught when a 10.2 cm mesh opening is used, according to gillnet selectivity analysis (Jiménez, 1999), so it mesh opening is recommended in order to protect the reproductive potential of the stock, aid to recovery its population and to achieve a better yield per recruit. Also, a decrease in the fishing effort to five nets per fishermen is recommended or at least prohibiting higher fishermen numbers.

Moreover, it would be recommendable to be cautious with repopulation programs due to the risk of affecting the genetic pool of the tilapias. The degree of consanguinity in the Infiernillo is considerable (Barriga-Sosa *et al.*, 2004), because all tilapia introductions have come from a reduced number of progenitors and the renovation of the stock is null. Therefore it is advisable to do genetic studies with the objective of improving future genetic and fishing bases to obtain better tilapia exploitation.

Although the models' limitations include the supposition of constant recruitment and natural mortality, they were useful in detecting the deteriorated status of the tilapia fishery in the Infiernillo reservoir and demonstrating the risk of surpassing the new point of equilibrium. Consequently, the implementation of management rules for this reservoir is urgent.

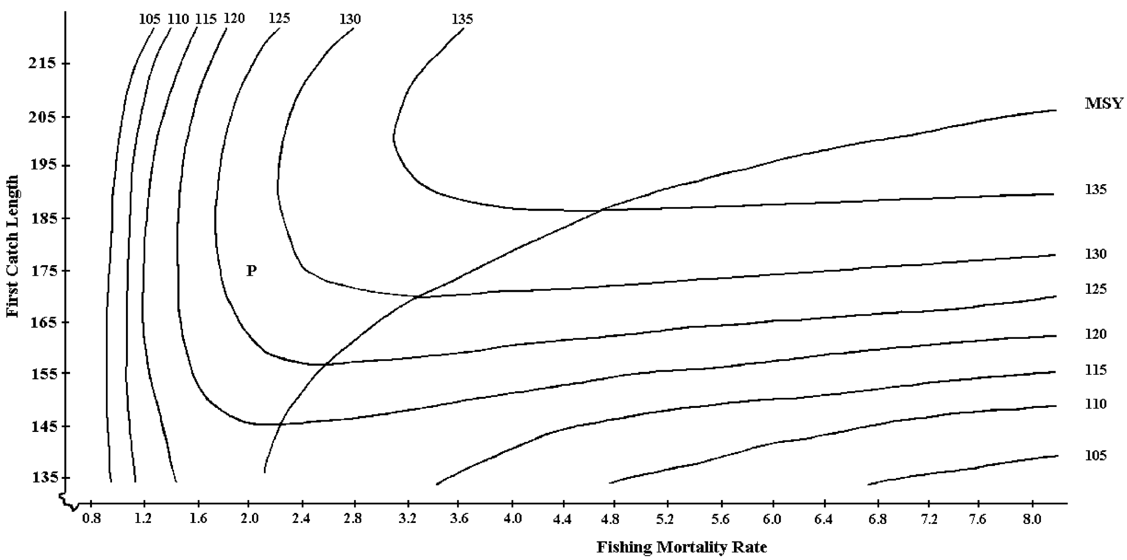


Figure 4. Isoplets of yield (g/recruit) for *Oreochromis aureus* in the Infiernillo reservoir. Fishery status in 1993 (P); maximum sustainable yield (MSY)

The tilapia fishery in Infiernillo faces similar problems as the tilapia fishery around the world, according to Petr (1987), Ochumba *et al.* (1992), Crul and Roest (1995) and Remane (1997). Therefore the methodological sequence used here may be useful for evaluating other reservoir fisheries, monitoring changes in the fishing intensity, predicting fish production and proposing their precautionary management.

Finally some considerations about the models are: Schaefer and Fox models are based on the inversely proportional relations between catch per unit effort and effort, but the first considers a certain effort level in which catch per unit effort is zero, while in Fox model, catch per unit effort is larger than zero for any value of effort. Therefore the election between these models is only important when relatively high effort values are observed (Sparre & Venema 1995). The analytical models are complementary, while Cohort Analysis gives a detailed feature of the stock, Beverton and Holt model produces results in terms of yield per recruit, and Thompson and Bell throw absolute values of yield and incorporate economic value of the fishery. All of them are usefully to forecast the stock status subject to different fishing patterns.

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