Potential Yield of South Asian Small Reservoir Fisheries

Final Report
Fisheries Management Science Programme
Overseas Development Administration

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EXECUTIVE SUMMARY

(1) Fisheries in many Asian reservoirs are culture-based, i.e. dependent on the regular stocking of seed fish.

(2) The project has substantially improved the conceptual understanding of culture-based fisheries. It has provided qualitative guidelines for the management of such fisheries, and tools for their quantitative assessment.

(3) A population dynamics model for culture-based fisheries has been developed. The model incorporates simple sub-models for the two key population processes of density-dependent growth and size-dependent mortality.

(4) Stocking and harvesting regimes for perennial and seasonal culture-based reservoir fisheries have been evaluated quantitatively using the population model.

(5) A quantitative assessment method developed on the basis of modelling results has been tested on stocking and catch data from a Chinese reservoir.

(6) The role of multiple uses in the management of communal small reservoirs has been studied in Northeast Thailand.

(7) A need for further research has been identified in the following areas: bio-economic modelling of culture-based fisheries, design of adaptive management policies, sampling for stock assessment, options in seed production, relationship between access rights and the provision of inputs for fish production, and management of small reservoirs for multiple objectives.

Final Report

CONTENTS

1 Objectives of the project

The aims of the project as specified in the memorandum were to estimate the yield of capture fisheries based on stock enhancement programmes in small reservoirs, and to assess the opportunities for enhancement of fish production through optimum stocking and harvesting strategies.

The following objectives were defined in the project memorandum:

(a) Identify constraints to fish production

(b) Describe interventions required to increase production

(c) Examine land and water use and assess compatibility with possible interventions

(d) Analyse social opportunities and constraints linked to interventions

(e) Assess environmental impacts of interventions

(f) Ensure that the proposed fish management strategies will have flexibility and be sustainable

Following an initial review of the literature, the project concentrated on two areas of research:

(1) Development of quantitative methods for the assessment of culture-based reservoir fisheries (addressing objectives a, b and f).

(2) Case studies of selected Asian reservoirs, to evaluate the quantitative methods developed, and to analyze the socio-economic and environmental constraints and opportunities linked to culture-based fisheries (addressing all objectives, but particularly c,d and e). The regional scope of the project has been extended from South Asia to Asia in general, as similar production systems are found throughout Asia, and important collaborative links could be formed with institutions in China and Thailand.

2 Work carried out

An initial review of the literature identified the lack of appropriate assessment methodology for culture-based reservoir fisheries as an important constraint to their successful development. The work plan was developed accordingly, concentrating at first on the population dynamics modelling of culture-based fisheries, and later on the development of practical methods for the biological as well as socio-economic assessment of such fisheries.

Mathematical models were developed for the two key population processes in culture-based fisheries, density-dependent growth and size-dependent mortality. Both models were tested on data sets available from the literature. The growth and mortality models were combined in a length-structured population model for culture-based fisheries. This very general population model was subsequently used to explore the effects of various management strategies on the yield of both seasonal and perennial reservoir fisheries.

Field studies were originally planned to be conducted jointly with the project "Effects of parasitism on the yield of small reservoir fisheries", utilizing established collaborations of the latter project with two institutions in India. The envisaged collaboration with the Central Inland Capture Fisheries Research Institute in Barrackpore did not materialize, while the collaboration with Mangalore Fisheries College in Karnataka was subject to a substantial delay. The work in Karnataka was carried out and funded entirely under the project "Effect of parasitism on small reservoir fisheries", which limited the scope and extent of the fieldwork.

As a consequence of the difficulties encountered in the planned collaborations, new links were established with institutions in China and Thailand. The Zhejiang Institute of Freshwater Fisheries in Huzhou, P.R. China, agreed to compile long-term stocking and catch data records for three medium size reservoirs in Zhejiang Province. Two data sets have been received, and are currently being analyzed. In Thailand, a collaborative project on small communal reservoirs has been established in collaboration with the Asian Institute of Technology Aquaculture Outreach, and the Royal Thai Department of Fisheries. The scope of this project is relatively broad, addressing both biological and socio-economic issues, and making use of the complementary expertise of the institutions involved. Fieldwork has started in February 1994, and has yielded a wealth of information which has not yet been fully analyzed. The field studies are being continued under the follow-up project "Culture fisheries assessment methodology" (R 5958).

Oral presentations on the project results were given at the following institutes or conferences:

- Zhejiang Institute of Freshwater Fisheries, Huzhou, P.R. China (28/8/93)
- AADCP Workshop on "Types of Lakes and Reservoirs in SE Asia and the Ecological Constraints on the Enhancement of their Fish Production", Melaka, Malaysia (21/10/93),
- International Center for Living Aquatic Resources Management, Manila, Philippines (4/11/93)
- European Inland Fisheries Advisory Committee, Working Party on Stocking, Thonon, France (15/11/93)
- MRAG/AIT/DOF communal pond project workshop, Udon Thani Freshwater Fisheries Research Centre, Udon Thani, Thailand (8-9/3/94)
- Conference on "Stock Assessment in Inland Fisheries", University of Hull, U.K. (12/4/94).

During the project, a substantial report has been produced and distributed, two manuscripts have been submitted for publication in scientific journals, and a third manuscript is in preparation:

Lorenzen, K. 1993. Assessment and Management of South Asian Small Reservoir Fisheries: A Population Dynamics Approach. London: MRAG Ltd. 120 pp.

Lorenzen, K. subm. A simple von Bertalanffy model for density-dependent growth, with an application to extensive aquaculture. Submitted to Aquaculture.

Lorenzen, K. subm. Population dynamics and management of culture-based fisheries. Submitted to Fisheries Management and Ecology.

Lorenzen, K. in prep. Size and mortality in fish: a comparison of ecosystems. To be submitted to Journal of Fish Biology.

More publications are expected to result from the ongoing collaborations in Thailand, China and India.

3 Results

3.1 Development of quantitative methods

3.1.1 Population dynamics modelling of culture-based fisheries

A population dynamics model for culture-based fisheries has been developed. The model is based on mathematical descriptions of the two key processes operating in stocked cyprinid populations: density-dependent growth and size-dependent mortality.

The model for density-dependent growth has been developed on the basis of von Bertalanffy's theory of growth. The model has been tested successfully in the analysis of carp growth experiments in extensive aquaculture. The three parameters of the model can be interpreted biologically, and at least one parameter can be estimated a priori from comparative studies.

The mortality-size relationship in freshwater fish has been studied empirically, using a large set of data retrieved from the literature. It was found that mortality can be described as a power function of weight, and that the mortality-size relationship in freshwater fish is not significantly different from that in marine fish (where it has been studied earlier by other authors).

The process models for growth and mortality have been combined in a size-structured matrix population model for culture-based fisheries. This general model can be used to simulate the effects of any possible stocking and harvesting pattern on the production from a culture-based fishery.

3.1.2 Theoretical evaluation of stocking and harvesting in perennial reservoir fisheries

Optimal stocking and harvesting in a perennial reservoir fishery are interrelated, and must be considered together in management. Maximal biological production is achieved by stocking at a high density and harvesting at the smallest marketable size. If stocking density is limited by the availability of seed, fish must be allowed to grow to a bigger size to achieve the best possible production from the seed stocked.

If overfishing occurs in a culture-based fishery, this can be averted by an increase in stocking density, which will give a higher level of production for the same level of effort. If fishing effort is low (as is the case in many reservoirs), the fishery is easily overstocked, leading to stunting of the population and increased mortality. The best option then is to increase fishing effort, alternatively stocking density can be reduced. In a developing reservoir fishery, increases of fishing effort and stocking density should go hand in hand.

Seed fish over a wide range of sizes can yield a similar level of production if stocked at the appropriate density. Small seed fish must be stocked at much higher densities than large seed fish. However, the biomass of large seed fish stocked at optimal density is much higher than the biomass of small seed fish stocked at the respective optimal density. This has two implications: First, if large seed fish are stocked, a higher biomass needs to be produced and handled. Second a higher biomass stocked initially limits the production potential of the population. These results indicate that the stocking of small seed fish can sometimes be a better option, particularly when seed production is limited by the capacity of farms to rear advanced fingerlings.

The production achieved from the stocking of large seed fish is also particularly sensitive to stocking density. Stocking of small seed fish is therefore more likely to yield a good production if there is considerable uncertainty regarding the optimal stocking density.

3.1.3 Theoretical evaluation of stocking and harvesting in seasonal reservoirs

Seasonal reservoirs fall dry during the dry season, which limits physically the duration of the growth period. Harvesting is usually confined to the end of the growth period, in which case the stocking density determines directly the average size of fish at harvesting. The highest biological production is achieved at stocking densities which produce fish at or just above the smallest marketable size.

If the physical growth period is sufficiently long, production may be enhanced by either (a) producing fish in two complete cycles of stocking and harvesting, or (b) sequential harvesting of fish above a minimum size throughout the growth period. Two production cycles are preferable if fish suffer a high natural mortality in the water body, because the time span between stocking and harvesting can be reduced. If natural mortality is low, sequential harvesting of large fish yields a higher production. The beneficial effects of both options are very sensitive to stocking density: if the appropriate stocking density cannot be attained due to lack of experience, two cycles or sequential harvesting are likely to yield less production than a single cycle with total harvesting.

3.1.4 Adaptive management

The population model for culture-based fisheries can be used to predict optimal stocking and harvesting schedules for a fishery, provided that model parameters can be estimated from the available data. In practice, such data is often insufficient to estimate parameters with the necessary degree of accuracy. In this situation, judicious experimentation with stocking or harvesting schedules can improve parameter estimates and allow the optimization of both stocking and harvesting. A management strategy that entails systematic experimentation in order to gain crucial information is called adaptive management. In culture-based fisheries, adaptive management allows a rapid improvement of stocking and harvesting schedules and carries very little risk, as it is usually possible to devise experiments that are likely to simultaneously provide information and increase yields. The theoretical evaluation of stocking and harvesting schedules using the population model also provides important insights into the design of adaptive management policies.

3.2 Case studies

3.2.1 Small communal reservoirs in NE Thailand

Small communal reservoirs in NE Thailand serve a variety of purposes: irrigation, domestic water supply, harvesting of fish, invertebrates and water plants, and buffalo wallowing. The stocking of fish in communal reservoirs has been promoted by the Thai Fisheries Department, and has met with varying success.

A baseline survey of communal reservoirs has shown that the majority of these water bodies are managed extensively for fish production, with stocking and some fertilization, but no feeding. The baseline survey has also demonstrated that the development of culture-based fisheries often interferes with other uses of the reservoir. Traditional rights to the harvesting of wild animals and plants from the pond are often restricted to protect the stocked fish. In some cases, inadequate fertilization and stocking have led to a deterioration in water quality, with the consequence that water from the reservoir is no longer used for domestic purposes.

The analysis of stocking and catch data has shown that the current species combination and stocking densities are inadequate to make full use of the natural production potential of the reservoirs. Improvements in the stocking densities have been recommended, and are going to be tested in a management experiment in the next production period.

The natural productivity of individual small reservoirs differs widely, and so does their importance for uses other than fish production. Fishery management of small reservoirs must account for these local conditions. This requires a participatory approach to research, and the extension of assessment methods rather than predefined production technologies.

3.2.2 Medium-size reservoirs in Zhejiang Province, P.R. China

The analysis of stocking and catch data from the 460 ha Hu Shan Reservoir has shown an increase in yield from less than 10 to more than 200 kg/ha, following the development of a culture-based fishery. Harvesting of the fishery is highly efficient, and a yield per recruit analysis has shown that the stock was growth overfished throughout the period for which data is available. This indicates that the fishery is understocked, and that an increase in stocking density would further increase yields.

The case study of Hu Shan Reservoir has also shown a need for efficient adaptive management policies, and a bio-economic model for culture-based fisheries.

3.2.3 Irrigation reservoirs in Karnataka, India

Catch data has been collected from one large irrigation reservoir in Karnataka, Vanivilas sagar (8000 ha). Stocked species contribute more than 35% to the yield of the fishery. Fishing effort is low, indicating that production could be increased by a coordinated increase of both fishing effort and stocking densities. At present, only six months of catch data are available. The estimation of growth parameters from the data using length frequency methods has proved difficult, due to the selectivity of the fishing gear used. This points to a common problem in small-scale reservoir fisheries, and calls for the development of more efficient sampling techniques for the assessment of such fisheries.

4 Implications of the results for achieving the objectives

The implications of the results for achieving the objectives are detailed below, separately by objective:

(a) Identify constraints to fish production

The project has identified major constraints to fish production from small and medium size reservoirs, namely: inappropriate stocking and harvesting regimes adopted largely due to lack of assessment methodology, conflicting uses of the reservoir, and unsatisfactory distribution of benefits from communal culture fisheries.

(b) Describe interventions required to increase production

This objective has been achieved. The population model developed has for the first time allowed a rigorous quantitative evaluation of management strategies for culture-based fisheries. The modelling study has also made important contributions to the development of adaptive management strategies for culture-based fisheries.

(c) Examine land and water use and assess compatibility with possible interventions

This objective has been partly met, in that the baseline survey of small reservoirs in Northeast Thailand has identified a number of use conflicts relating to culture fisheries development.

(d) Analyze social opportunities and constraints linked to interventions

This objective has not been met, due to the late start of the fieldwork. Only some very general observations on social opportunities and constraints have been made.

(e) Assess environmental impacts of interventions

This objective has not been met, again due to the late start of the fieldwork.

(f) Ensure that the proposed fish management strategies will have flexibility and be sustainable

This objective has been largely achieved. The adaptive approach proposed ensures that the management of culture-based fisheries is flexible with regards to biological, ecological, and socio-economic conditions. The long-term sustainability of culture-based fisheries could not be assessed in this project, due to the failure to meet objective (e).

5 Priority tasks for follow up

A bio-economic model for culture-based fisheries should be developed on the basis of the population model. This would provide qualitative guidelines for the economic assessment of culture fisheries, and a tool for quantitative assessment where relevant data are available.

The population model for culture-based fisheries could be expanded to include natural recruitment in the stocked population. This would make the model more relevant to the culture-enhanced fisheries found in some large reservoirs.

Efficient adaptive management policies for culture-based and culture-enhanced fisheries should be designed. Sampling strategies and methods for the estimation of model parameters from stocking, catch, and survey data need to be improved, to ensure that a maximum of information can be obtained from limited sampling effort.

Options for seed production in culture-based and culture-enhanced fisheries need to be evaluated in economic terms.

In small communal reservoirs the focus of research should be expanded from "fish production" to "fisheries management for multiple objectives". Participatory appraisals of reservoir use and fish production options should form a key part of such research.

Simple assessment methods must be developed for small communal reservoir fisheries. This requires a combination of quantitative analysis with the farming systems research and extension (FSR&E) approach, to arrive at appropriate assessment methods. The diversity of communal small reservoirs makes it imperative to extend assessment methods rather than pre-defined culture technologies.

A framework for the biological, socio-economic and environmental appraisal of culture-based fisheries development plans should be developed.

The tasks identified are being taken up by the current project "Culture fisheries assessment methodology" (R 5958).

OUTLINE OF RESULTS OBTAINED

1 Background

Reservoir construction for irrigation and domestic water supply dates back more than 2000 years in some parts of Asia. This century has witnessed an unprecedented increase in the number, size and total surface area of reservoirs throughout Asia. Despite the long tradition of reservoir construction in Asia, reservoir fisheries have developed only very recently, after 1950. Natural fish production from Asian reservoirs is generally low, due to the paucity of indigenous lacustrine fish species that could colonize the reservoir habitat. After 1950, increased fish production from reservoirs has been achieved in two different ways. Lacustrine African tilapia have been introduced to establish self-perpetuating populations in some Asian reservoirs, notably in Sri Lanka. China, India and Thailand on the other hand have developed reservoir fisheries as extensive aquaculture systems or culture-based fisheries, maintained by regular stocking of farm produced seed fish.

Reservoir fisheries for introduced, self-perpetuating populations can be assessed using the conventional tools of fish stock assessment. Culture-based fisheries on the other hand pose unique problems and require specific methods to assess not only the harvesting, but also the stocking regime and their interrelation. Little relevant methodology is available at present, and the management of culture-based fisheries remains largely haphazard. Given the extent of culture-based fisheries and the amount of resources committed to seed production by government agencies, there is an urgent need for the management of culture-based fisheries to be put on a rational foundation. Consequently, the development of assessment methods for culture-based fisheries has been given highest priority in the project.

Complementing the largely theoretical work on the population dynamics modelling and assessment of culture-based fisheries are three case studies in Thailand, China and India. The purpose of the case studies was to obtain an overview of Asian reservoir fisheries and their problems, to assess the environmental and socio-economic constraints and opportunities linked to culture-based reservoir fisheries, to test the newly developed assessment methodology in practice, and to assess needs for further research.

2 Population dynamics modelling of culturebased fisheries

A population dynamics model for culture-based fisheries has been developed which is conceptually simple, yet able to address all the key management problems of such fisheries within a unified framework. The population model comprises two sub-models for the key processes of density-dependent growth and size-dependent mortality. Density-dependence in growth determines the optimal stocking density, and size-dependence in mortality pertains directly to the optimal size of seed fish.

2.1 Growth

The density-dependent growth model is based on the von Bertalanffy theory of growth; it expands on the concepts used by von Bertalanffy to derive the growth function commonly used in fisheries. In the von Bertalanffy growth function, the asymptotic length is related to the building up of body materials (anabolism), while the growth rate parameter k is related to the breakdown of body materials (catabolism). Density-dependent growth in fish is the result of intraspecific competition, mainly competition for food. Competition is expected to have a direct effect on anabolism, but not on catabolism. Hence in the density-dependent growth model, asymptotic length is expressed as a linear function of population biomass density. The resulting growth model has three parameters: the conventional growth rate parameter K, the limiting asymptotic length in the absence of competition, and a competition coefficient which gives the decrease in asymptotic length per unit increase in biomass density. Both new parameters can be interpreted biologically. The asymptotic length in the absence of competition is related to the productivity of the water body. The competition coefficient signifies the intensity of competition within the population, it relates to population structure and the degree of dietary overlap between individuals.

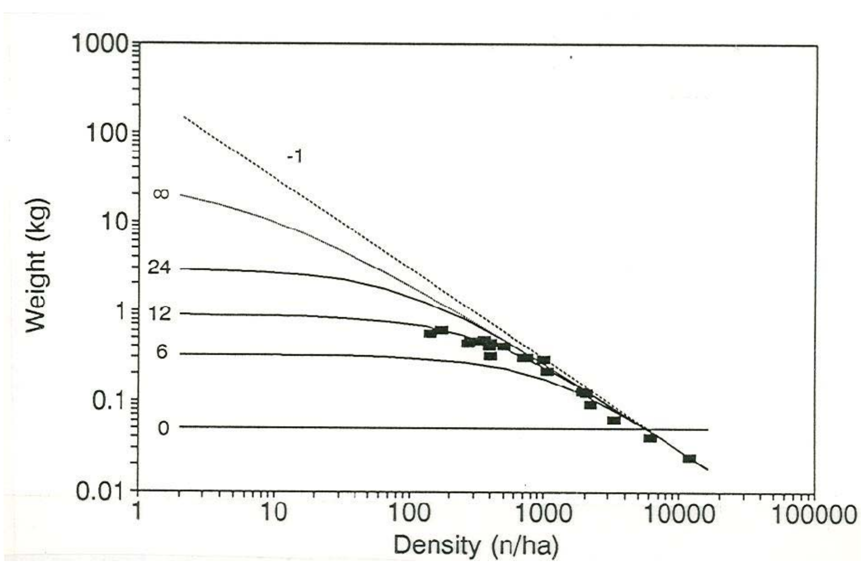

Figure 1. Density-dependent growth model. Predicted weight of carp in single cohort culture, after 6, 12 and 24 months, and asymptotic weight W as a function of stocking density.
A straight line of slope -1 denotes constant final biomass density Data points indicate the observed weight of common carp after 12 months in an extensive aquaculture experiment.

The growth model has been tested on data from extensive pond culture experiments, and has been shown to provide a good description of growth in both single cohort and mixed age populations. Fig. 1 shows model predictions of weight at age in single cohorts of common carp stocked at different densities, together with experimental data. Note logarithmic scaling on both axes. Solid lines denote weight at 0, 6, 12, and 24 months after stocking, and asymptotic weight as a function of density. The dashed line of slope -1 denotes constant biomass. All cohorts are stocked at a mean individual weight of 0.05 kg. At low densities, growth in weight is rapid and almost independent of density. As density increases, weight at age decreases, and asymptotic weight is approached more rapidly. At a density of 500 fish per hectare, for example, 24 months old fish have approached the asymptotic weight for the corresponding biomass density very closely. At very high densities, asymptotic weight is approached closely within a few months. The model predictions are in good agreement with experimental data, as shown by the observed weights attained after a 12 months growth period.

2.2 Mortality

The mortality-size relationship of fish in the marine pelagic ecosystem has been the subject of earlier theoretical and empirical studies. In this project, the mortality-size relationship has been studied empirically for freshwater fish in lakes, rivers, and aquaculture ponds. An extensive data set on mortality in relation to size has been retrieved from the literature. A nonparametric regression method was used to estimate mortality-size relationships from the new data set, and to re-analyze data for the marine pelagic system.

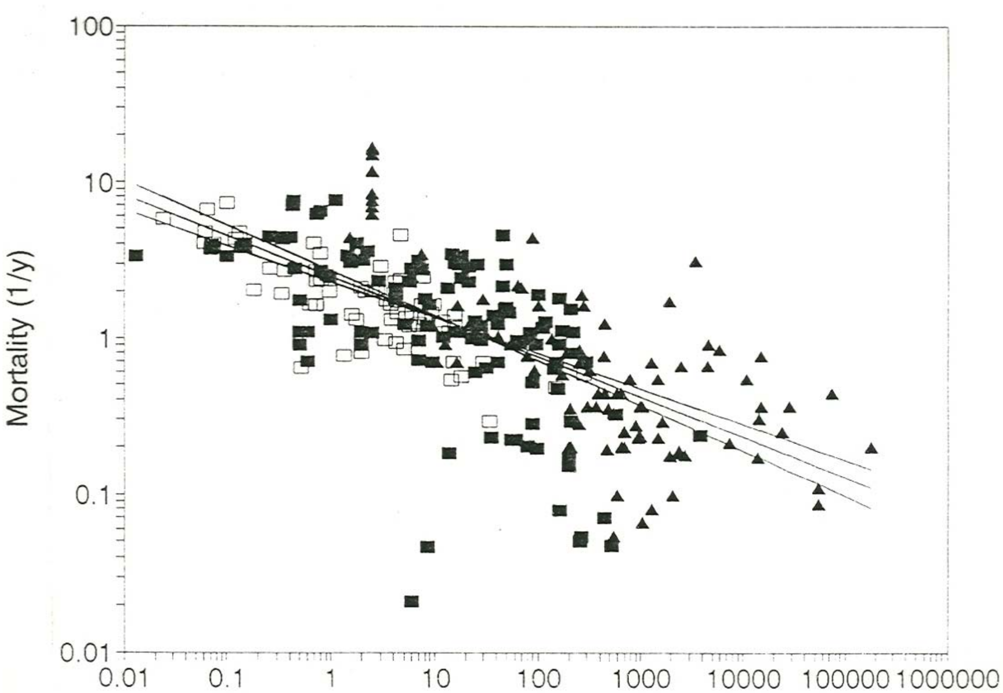

Figure 2. Mortality-size relationship of fish in natural ecosystems. Data from (■) lakes, (□) rivers, and (▲) the marine environment.
The fitted regression line for the complete data set is also shown, together with 95% confidence limits for the slope.

In all ecosystems, mortality can be described by a power function of weight. No significant difference was found between ecosystems, and a joint mortality-weight relationship has been estimated for all natural ecosystems. In Fig. 2, the mortality-weight data for natural ecosystems is shown on logarithmic scales, together with the fitted regression line, and 95 % confidence limits for the slope (i.e. the exponent of the power function). The exponent of the mortality-size relationship is of particular interest in the management of culture-based fisheries, because it is the change of mortality with increasing size rather than the absolute value of mortality that determines the optimal size for stocking. The estimated exponent is -0.258, with a 95% confidence interval of [-0.289, -0.229].

2.3 Population model

The models for density-dependent growth and size-dependent mortality are combined in a length-structured matrix population model. The fish population is divided into length groups, and the model projects population and catch numbers-at-length over time. Such a model is most general in that it allows any possible stocking and harvesting schedule to be simulated, but it is also very demanding computationally. More simple and computationally less demanding population models have been constructed for particular, more limited applications. All population models use the same underlying process models for density-dependent growth and size-dependent mortality.

3 Evaluation of management strategies using the population model

The population model is now used to evaluate theoretically the effects of different management strategies on culture-based reservoir fisheries. Two different types of fishery are considered: perennial fisheries operate in reservoirs which maintain sufficient water for fish production all year round, while seasonal fisheries operate in water bodies that fall dry regularly during the dry season. Perennial reservoirs offer the widest range of possibilities in terms of stocking and harvesting strategies. In seasonal reservoirs, the duration of the growth period is physically limited, and this also constrains the possible management strategies.

In the following sections, management strategies are explored separately for perennial and for seasonal reservoirs. The parameter values used in the model simulations are representative of stocked carp populations in a medium-size perennial reservoir, and a small seasonal reservoir. Small, seasonal reservoirs tend to be more productive than larger perennial water bodies, and this is accounted for in the different parameter sets used for the perennial and the seasonal fishery.

3.1 Stocking and harvesting of perennial reservoirs

The response of the model population in a perennial reservoir to various stocking and harvesting regimes is explored in the following sections, separately for stocking density, size at harvesting and fishing mortality in relation to stocking density, and the size of seed fish.

3.1.1 Stocking density

The influence of stocking density on production and the recapture rate of stocked fish is illustrated in Fig. 3. The mean length of seed fish is constant at 5 cm. Gear selection length is 30 cm, i.e. all fish longer than 30 cm are caught if they encounter the gear, while all smaller fish can escape. Fishing mortality is taken to be very high, so that fish are harvested immediately after reaching the selection length. The average weight of fish in the catch then is about 0.7 kg.

The biomass stocked always increases proportionally to stocking density in numbers, because the mean weight of seed fish is constant at about 3.5 g per individual. The biomass harvested increases almost proportionally to stocking density at low densities, but the rate of increase then declines as stocking density increases further. This reflects the density-dependent reduction in individual growth, and the consequent increase in natural mortality. The maximal biomass harvested is 67.6 kg ha^{-1} y^{-1}, at a stocking density of 560 ha^{-1} y^{-1}. The biological production of the fishery is equal to the biomass harvested minus the biomass stocked. Production reaches a maximum when the slope of the "biomass harvested" curve is equal to that of the "biomass stocked" line, at a stocking density slightly lower than that at which the maximal biomass is harvested. If stocking density is increased beyond 560 ha^{-1} y^{-1}, this results in a decline of both biomass harvested and production: the fishery is overstocked. At high population densities, fish grow slowly and consequently suffer higher natural mortality. This is apparent in the recapture rate, the fraction of stocked fish which are recaptured in the fishery. At very low stocking densities, the recapture rate is highest (about 30%) due to the fast growth of individuals. The recapture rate is much lower (about 15 %) in the region of optimal stocking density, and then declines further when the fishery is overstocked. Clearly, the return per seed fish stocked is highest at low stocking density. However, the overall production optimum is reached when the recapture rate and the consequent return per seed fish are at an intermediate level.

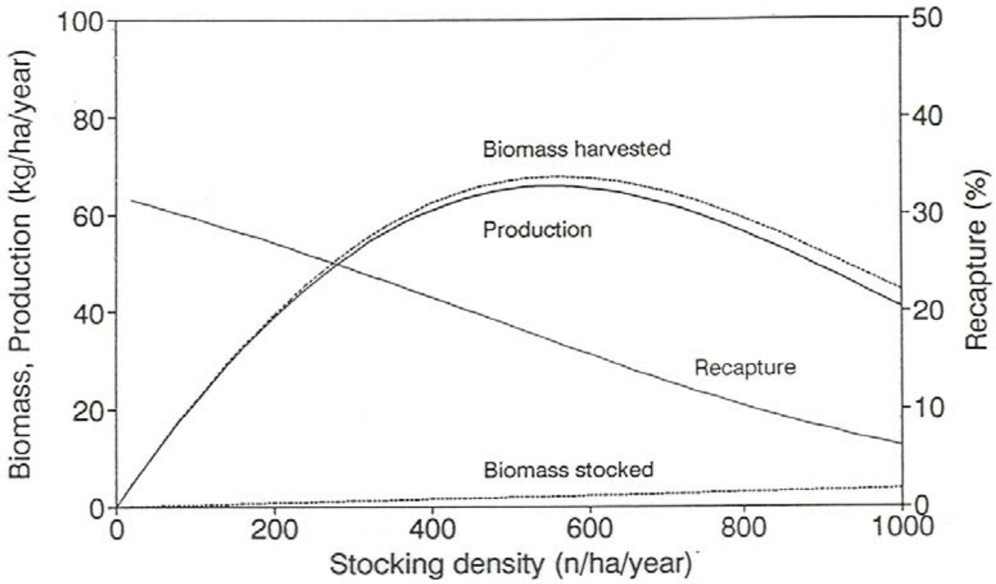

Figure 3. Stocked biomass, harvested biomass and production as a function of stocking density in numbers. Also shown is the fraction of seed fish recaptured in the fishery. A gear selection length of 30 cm and a very high fishing mortality are assumed.

3.1.2 Size at harvesting

The optimal stocking density in a culture-based fishery is dependent on the size of the fish harvested. In Fig. 4, production is shown as a function of stocking density for gear selection lengths of 25, 30, 35 and 40 cm, corresponding to weights of about 0.4, 0.7, 1.1 and 1.7 kg respectively. Fishing mortality is again taken to be very high. The mean length of seed fish is constant at 5 cm.

At a selection length of 40 cm, the maximal production of 35 kg ha^{-1} y^{-1} is reached at a low stocking density of only 140 ha^{-1} y^{-1}. If stocking density is increased beyond this optimum, production declines rapidly and drops to zero before 300 ha^{-1} y^{-1} are reached. Moderate overstocking results in sub-optimal production due to slow growth and high mortality, but the fishery can still operate. If stocking density is increased further, the asymptotic length of the population will fall below the gear selection length. This brings about a qualitative change as catches drop to zero, and the fishery no longer removes biomass from the population. If stocking continues, the water body is literally "choked" with fish, resulting in a dense, stunted population. At a high gear selection length like 40 cm, the critical biomass is reached easily, and overstocking can be a serious management problem.

The maximal production at a selection length of 35 cm is 48 kg ha^{-1} y^{-1}, at a stocking density of 280 ha^{-1} y^{-1}. Obviously, the potential production increases with decreasing size at harvesting, but this production is achieved only at increasingly high stocking densities. For the harvesting sizes considered in this example, the overall production maximum is reached at the lowest selection length of 25 cm, at a stocking density of over 1000 ha^{-1} y^{-1}. Unless stocking densities are limited by the availability of seed, it is more productive to harvest fish at the smallest marketable size.

When stocking density is limited by seed supply, this also dictates the optimal harvesting size. For example, if stocking density is limited to 500 ha^{-1} y^{-1}, Fig. 3 shows that the optimal size for harvesting is about 30 cm (0.7 kg). In general, if stocking density is limited, the optimal size for harvesting may be much larger than the smallest marketable size.

If only large fish are marketable, it is counterproductive to stock at high densities. For example, if the smallest marketable size for catches from the model population was 1.1 kg (35 cm), no more than 280 seed fish of 5 cm length should be stocked per hectare and year.

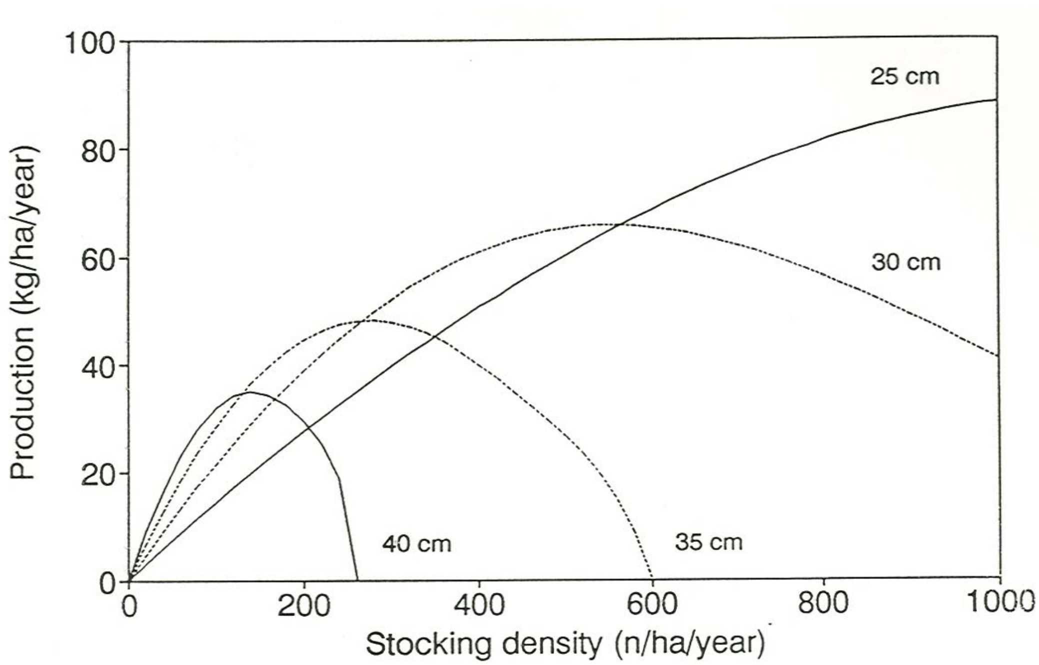

Figure 4. Production as a function of stocking density, for four different gear selection lengths between 25 and 40 cm. Very high fishing mortality.

3.1.3 Fishing mortality

The problem of fishing mortality is linked to the size at harvesting: the higher the fishing mortality for a set gear selection length, the lower the average size of harvested fish. This implies that a high fishing mortality calls for a high stocking density, and vice versa.

The combined effect of fishing mortality and stocking density on production is illustrated in Fig. 5, for a constant selection length of 30 cm, and a mean size of seed fish of 5 cm. Production contour lines indicate the combinations of fishing mortality and stocking density that give rise to the same levels of production. For example, a production of 40 kg ha^{-1} y^{-1} can be achieved by stocking 200 fish ha^{-1} y^{-1} and fishing at F=2.5 y^{-1}, or by stocking 600 fish ha^{-1} y^{-1} and fishing at just above F=2.0 y^{-1}. The heavy solid line (a) shows optimal stocking density in relation to fishing mortality. If stocking densities are above this line the fishery is overstocked, and a reduction in stocking density will increase production. The same effect can be achieved by an increase in fishing mortality. The heavy solid Line (b) shows the optimal fishing mortality in relation to stocking density. If the fishery is operated below this line, it is overfished and a reduction in fishing mortality will increase production. Alternatively, overfishing can be avoided by increasing stocking density. In this example, an increase in stocking density at fixed fishing mortality will improve production substantially, while a reduction in fishing mortality at fixed stocking density will have a more limited effect.

Both overstocking and overfishing can be averted by a change in either the stocking or the harvesting regime. The most suitable alternative depends on the current position of the fishery in its fishing mortality/stocking density plane.

As a rule, high stocking density requires high fishing mortality, and vice versa. In a developing culture-based fishery, it is important to increase both stocking density and fishing mortality in a balanced way.

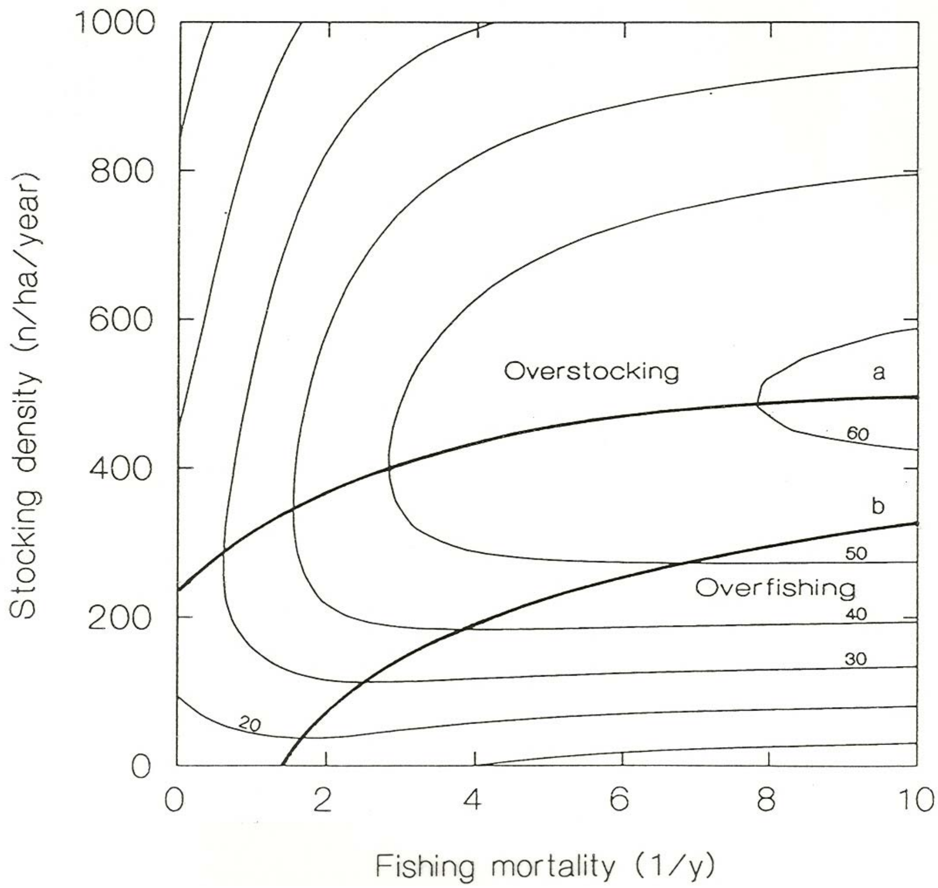

Figure 5. Production as a function of fishing mortality and stocking density, for a gear selection length of 30 cm. Labels of the contour lines indicate production in kg $ha^{-1}y^{-1}$. The heavy solid line (a) indicates optimal stocking density in relation to fishing mortality, line (b) indicates optimal fishing mortality in relation to stocking density.

3.1.4 Size of seed fish

Selecting the size of seed fish for stocking is a crucial aspect of the management of culture-based fisheries. Because mortality is size-dependent, the best recapture rate and hence return per seed fish is usually obtained by stocking large fish. However, large seed fish are expensive to produce and their use also has other implications which are illustrated for the model population in Figs. 6 and 7. The size of seed fish is varied between 3 cm and 11 cm, while harvesting with a constant gear selection length of 30 cm, and very high fishing mortality.

In Fig. 6, potential production is shown as a function of the length of seed fish, together with the stocking density and seed biomass required to achieve the potential production. Obviously, any size of seed fish within the range considered here can yield a similar level of production. There is a slight decrease of potential production with increasing length of seed, which is explained later.

The optimal stocking density, at which potential production is obtained, declines sharply with the size of seed fish, from over 1100 ha^{-1} for 3 cm to less than 300 ha^{-1} for 11 cm fingerlings. The form of this curve reflects the mortality-size relationship, and the steepest decrease in optimal stocking density occurs in the low size range. Increasing the size of seed fish from 3 to 5 cm reduces the number of seed required by more than 50%, while an increase in size from 9 to 11 cm reduces the numbers required by only 15%. The best size for stocking is likely to be in the intermediate range, striking a balance between the need to produce vast numbers of individuals, and the need to rear them to a large size.

Also shown in Fig. 6 is the total biomass of seed stocked at the optimal density in numbers. Large seed fish must be stocked at a much higher biomass than small fish: while 1 kg $ha^{-1}y^{-1}$ of 3 cm fish is sufficient to achieve maximal production, 11 cm fingerlings must be stocked at 9 kg $ha^{-1}y^{-1}$. The use of large seed fish implies the necessity to produce and stock a relatively high biomass of seed. This fact also explains the slight decline in production, which is defined as biomass harvested minus biomass stocked, with increasing size of seed fish.

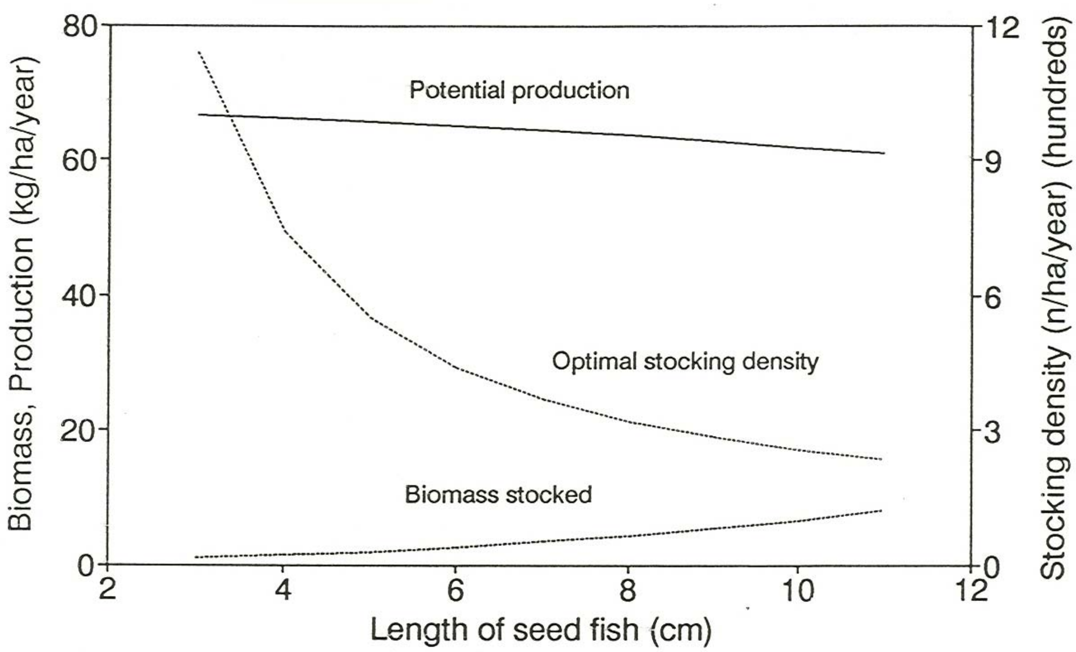

Figure 6. Influence of the length of seed fish on potential production, optimal stocking density and the corresponding biomass stocked.
Optimal stocking density is the density required to realise potential production. Gear selection length 30 cm, and very high fishing mortality

An important side-aspect of optimal seed size is the sensitivity of production to stocking at non-optimal densities. This is illustrated in Fig. 7, which shows the changes in production for stocking densities 50% below and above the optimum, for different sizes of seed fish. For 3 cm fish, 50% understocking reduces production to 80% of the maximum, while 50% overstocking reduces production to 88%. Production from 11 cm seed fish is much more sensitive, a 50% understocking reduces production to 66%, but the same percentage overstocking causes a reduction to 35% of the maximal production.

Production from large seed fish is therefore more sensitive to stocking density than production from small seed. Hence, if the optimal density is not known from experience, stocking small seed fish is more likely to yield good results than stocking large seed fish. Production from small seed is most sensitive to understocking, while the production from large seed is particularly sensitive to overstocking.

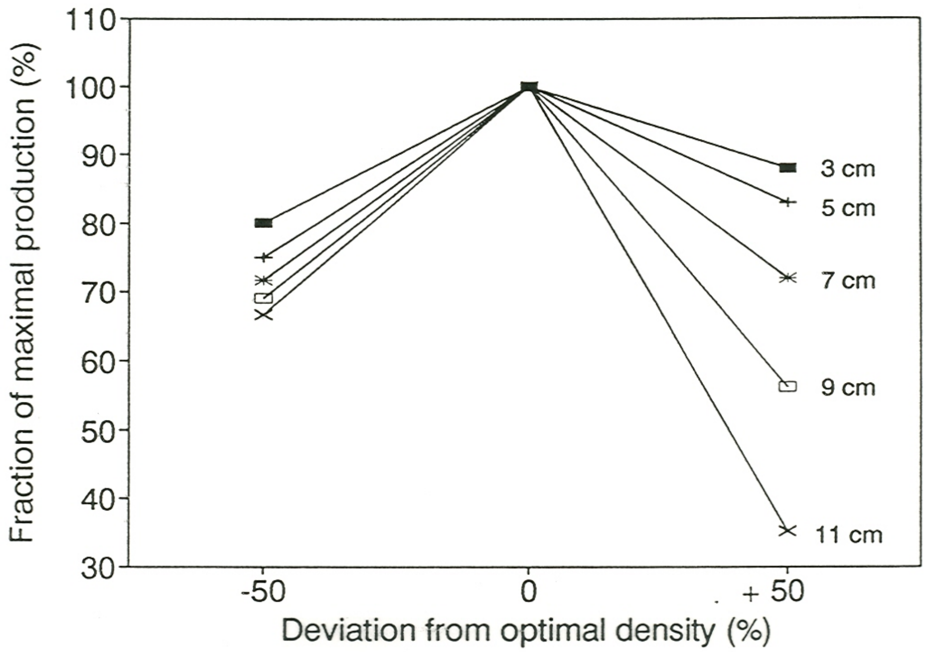

Figure 7. Sensitivity of production to sub-optimal stocking density, for different sizes of seed fish. The effect on production of a 50% deviation from optimal stocking density is shown. Gear selection length 30 cm, and a very high fishing mortality.

3.2 Stocking and harvesting of seasonal small reservoirs

In a seasonal small reservoir, the duration of the production period is physically limited. Nevertheless, several options are available with regards to stocking and harvesting schedules. The most simple way of managing a seasonal reservoir fishery is a single production cycle, with stocking and harvesting confined to short periods of time at the beginning and at the end of the production cycle. Alternatively, harvesting can be extended over a longer period in what is referred to a staggered or sequential harvesting. Finally, the production period can be split into two or three discrete cycles of stocking and harvesting. These three options and their benefits and problems are explored below, using the size-structured population model and a parameter set representing a carp population in a productive, seasonal reservoir.

3.2.1 Single production cycle with complete harvesting

In a single production cycle with complete harvesting at the end, stocking density determines directly the size of fish in the catch, and total production. This is demonstrated in Fig. 8, where the average individual weight in the catch, yield, and production are shown as a function of stocking density. Average weight declines and production increases continuously with increasing stocking density. The highest production is achieved if fish are produced as small as possible, at the minimum marketable size.

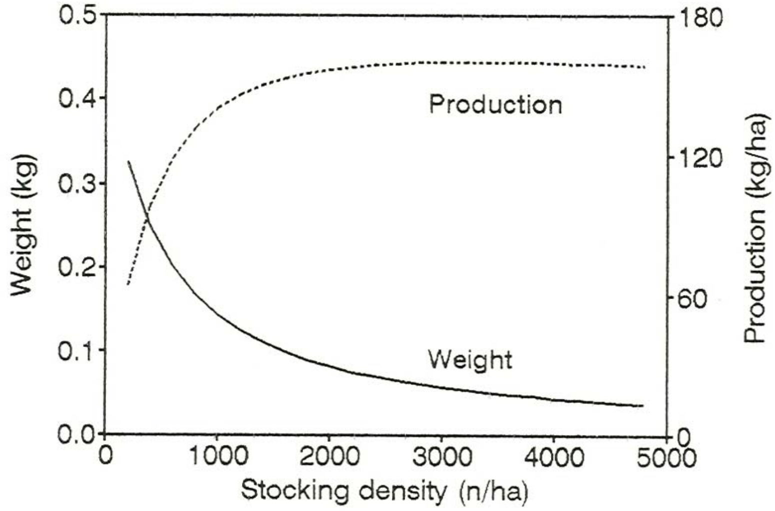

Figure 8. Influence of stocking density on average individual weight at harvesting and production in a seasonal reservoir fishery. Single, complete harvesting at the end of the production period.

3.2.2 Staggered harvesting

Under staggered or sequential harvesting, fish capture is effected over a period of several weeks or months, rather than limited to the end of the production cycle. Fish that have reached a marketable size are harvested continuously, thereby thinning the population and increasing the growth rate of the remaining individuals.

The effects of staggered harvesting at different gear selection lengths on individual weight in the catch, and on total production are illustrated in Fig. 9. At low stocking density without staggered harvesting, fish grow much larger than the gear selection lengths considered. Under staggered harvesting, these fish are caught soon after reaching the selection length of 15, 18, or 20 cm. Hence, at low stocking density, the average weight under staggered harvesting is almost constant, and lower than the weight reached under single harvesting. Staggered harvesting is clearly not beneficial at low stocking densities. The average weight under single harvesting declines with increasing density, and eventually falls below the average weight under staggered harvesting at any given selection length. Above this stocking density, staggered harvesting is advantageous because it increases the average size of the produce and hence production (Fig. 9 B) with respect to single harvesting. If density is increased further, the average weight under staggered harvesting approaches that under single harvesting; hence staggered harvesting leads to an increase in the average weight of produce over some limited range of stocking densities. This pattern is similar for all three selection lengths, but the effect of staggered harvesting is greatest at low selection lengths, i.e. when fish are harvested at a small size.

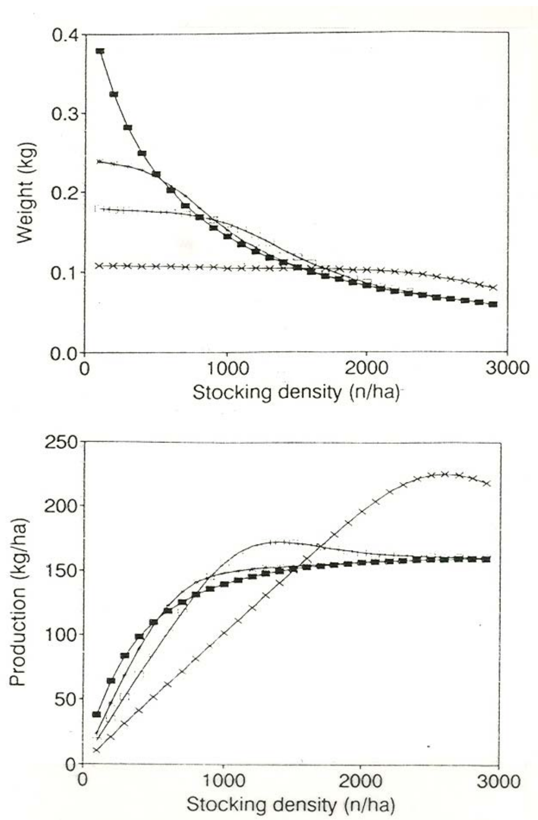

Figure 9. Effect of staggered harvesting on average individual weight and production from a seasonal reservoir fishery. (■) Single harvesting, and staggered harvesting at gear selection lengths (*) 20 cm, (□) 18 cm, and (x) 15 cm.

If fish of a certain size are to be produced under single harvesting, this is achieved by stocking at such a density that the desired average size is reached at the end of the production period. When fish are stocked at a higher density, they do not reach the desired average size. However, because a cohort comprises fish of a range of sizes, some fish at least are growing to the desired size before the end of the period. The harvesting of such individuals eases competition within the remaining population, and allows smaller fish to reach the desired size. Hence the average size of produce is increased with respect to single harvesting at the same stocking density. At very high stocking densities, very few or no fish will reach the desired size, and staggered harvesting can not take effect.

The beneficial effect of staggered harvesting on production is dependent on the duration of the production period, and on the mortality rate of the stocked population. In Fig. 10, maximum production with and without staggered harvesting is shown as a function of the duration of the production period, for no mortality (Fig. 10 A) and a moderately high size-dependent mortality (Fig. 10 B). The minimum period required to produce fish of marketable size in this example is 4 months.

In the absence of mortality (Fig. 10 A), production under both harvesting regimes increases steadily with the duration of the production period. The absolute and relative benefit of staggered harvesting also increases with the duration of the period. During a 4 months period, staggered harvesting incurs a production loss of 30%. A six months, there is a gain of 20%, which rises to 45% for a 12 months period.

At high mortality (Fig. 10 B), production under both harvesting regimes increases initially with the duration of the production period, but is about constant for periods of 8 months or longer. Regardless of the harvesting regime, it is not useful to extend the production period beyond 8 months.

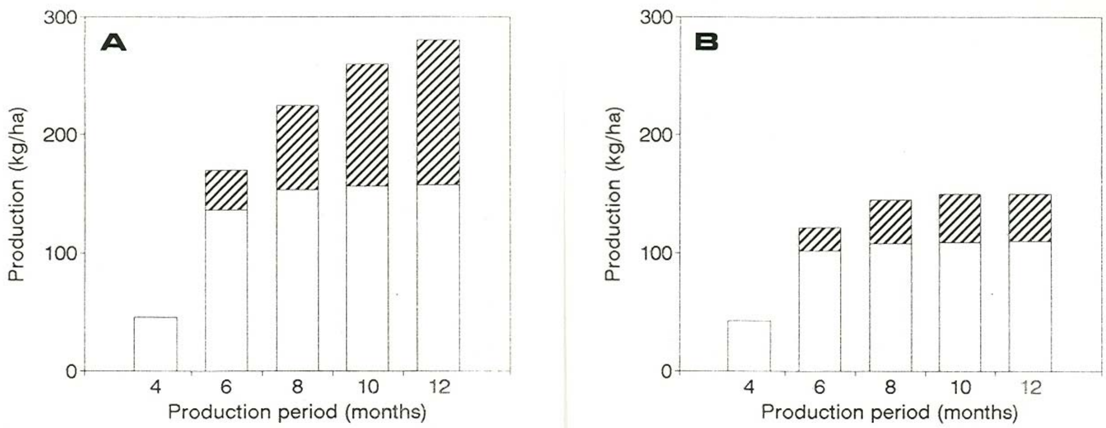

Figure 10. Effect of staggered harvesting on production, in relation to the length of the production period and the natural mortality rate. Hatched bars denote production gained by staggered harvesting. (A) No mortality, (B) Moderate mortality.

3.2.3 Multiple production cycles

The available growth period can be split into two discrete production cycles, provided that the period is long enough and that seed fish are available at the times of stocking.

The effect of splitting the production period into two separate cycles is shown in Fig. 11, for no mortality and a moderately high size-dependent mortality. The minimum period required to produce fish of marketable size is 4 months, hence only periods of 8 months or longer can be split into two cycles. In both cases shown here, splitting an 8 months production period into two cycles results in a loss of production, while the splitting of 10 or 12 months periods results in a considerable increase of production. The benefit of several production cycles is higher under a moderately high mortality (Fig. 11 B) than in the absence of mortality (Fig. 11 A): the gain in production is 56% and 85% during 10 and 12 months periods at moderate mortality, and 50% and 73%, respectively, in the absence of mortality.

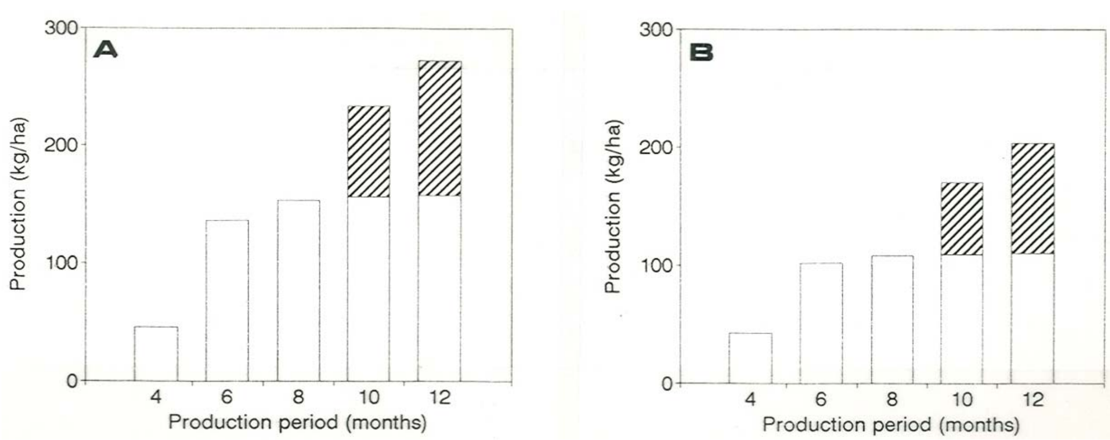

Figure 11. Effect of multiple production cycles on total production, in relation to the length of the growth and the natural mortality. Hatched bars denote production gained by splitting the growth period into two discrete production cycles. (A) No mortality, (B) moderate mortality.

3.2.4 Comparison of stocking and harvesting options

A number of qualitative conclusions can be drawn from the above modelling results. If the available production period is short, a single production cycle with complete harvesting at the end is the only management option. If the growth period is long, production can be increased by staggered harvesting, or by splitting the period into two discrete production cycles. Staggered harvesting is preferable if mortality is low, while multiple cycles are preferable if mortality is high.

An example of an overall comparison of different management options is given in Tab. 1, for a 10 months production period. In the absence of mortality, a single stocking with staggered harvesting yields the highest production. At a moderately high mortality, the maximum production is achieved in two discrete production cycles of 5 months each. Regardless of mortality, both options (staggered harvesting or two cycles) increase production substantially over the level that can be achieved in a single production cycle.

Table 1. Effect of various stocking and harvesting regimes on total production during a ten months growth period. Maximum production is given, subject to the constraint of a minimum average weight of 0.15 kg. The management patterns are: single and double cycles with complete harvesting at the end of cycle, and single stocking with staggered harvesting at a selection length of 18 cm.

	No mortality		Moderate mortality	
Regime	Production (kg/ha)	Stocking density (n/ha)	Production (kg/ha)	Stocking density (n/ha)
Single cycle (10 months)	156	1000	109	3400
Two cycles (5 months each)	234	1600	170	5400
Single cycle with staggered harvesting	259	1600	150	8000

3.3 Adaptive management of culture-based fisheries

In the previous Section, the population model was used to derive general insights into the dynamics of culture-based fisheries. This chapter is concerned with the application of the model in the quantitative assessment of particular fisheries.

3.3.1 Parameter estimation

Population parameters must be estimated in order to predict quantitatively the effects of management measures on a particular fishery. Some parameter values can be inferred from external information, while others can only be estimated from stocking and catch or survey data for the particular fishery.

The parameter K in the density-dependent growth model is the same as in the conventional von Bertalanffy growth function and can be inferred from comparative studies, but the parameters describing the density response in growth must be estimated for each fishery separately. This is possible only if data on individual growth is available for a range of biomass densities.

For the mortality-size relationship, *a priori* information on the value of the exponent can be gained from ecological theory and from empirical studies. The coefficient of the relationship can then be estimated from stocking and catch data. If both parameters of the mortality-size relationship are to be estimated directly, data must be available over a range of seed fish sizes.

3.3.2 The adaptive management approach

Although the model parameters can be estimated as outlined above, their values will often be subject to a high degree of uncertainty. This particularly applies to newly established fisheries, or to fisheries with no record of stocking and catch data.

However, the management of culture-based fisheries under uncertainty needs not be left to trial and error. Even under very high uncertainty, it is usually possible to adopt management measures which are likely to simultaneously improve production and yield important information, i.e. reduce uncertainty. A management strategy which serves both objectives is called adaptive management. Adaptive management entails judicious experimentation with stocking and harvesting regimes, and a systematic analysis of the outcome of such experiments.

A prerequisite for adaptive management is the collection of stocking and catch data, so that the present status of the fishery and the effects of any changes in management can be assessed. Stocking and catch data can be obtained easily from seed production centres and regular (not necessarily frequent) sampling at landing sites. In fisheries using highly selective gear like gillnets, surveys using less selective gear or multi-mesh gillnets may provide better information than extensive catch surveys. It may also be useful to mark certain batches of fingerlings, e.g. by fin clipping. This is likely to improve the precision of growth parameter estimates.

The following example illustrates the adaptive approach to management. Consider a fishery for which stocking and catch data is available for one production cycle (time between stocking and harvesting of a cohort). Density-independent growth and mortality parameters can be estimated from the data, and from empirical models. A yield-per-recruit analysis will indicate whether the population is overfished or underfished. If the analysis indicates overfishing, an increase in stocking density will improve production. However, because the growth response to changes in density is not known, it is not possible to predict by how much the density should be increased. The choice of a new stocking density involves a tradeoff between the gain of information and the risk of reducing yield. A moderate increase in density will almost certainly increase yield, but it may not produce a strong growth response. A strong increase in density will produce a strong response and thus yield better information, but it may lead to overstocking, which would require the mass removal of undersized fish. Suppose stocking density is increased by a moderate amount in the following production cycle, and the analysis repeated. Growth parameters are now available for two different population biomass densities, which gives an indication of the growth response to density. On this basis, it is possible to obtain a first quantitative indication of how stocking density should be changed in order to optimize production for a given level of fishing mortality. The predicted optimal stocking density is, of course, still subject to considerable uncertainty. Hence the effects of the new density must again be monitored and analyzed.

Adaptive management is a continuous process, it is not finished once the current stocking and harvesting regimes appear to be optimal. Monitoring continues to detect changes in the ecology of the fishery, or in its exploitation. Moreover, management objectives are likely to change, for example in response changing to socio-economic factors. Adaptive management entails a systematic and efficient way of responding to such changes, thereby ensuring the sustainability of the culture-based fishery.