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# A MODEL OF THE EFFECTS OF RIVER FLOW REGULATION ON THE SPAWNING EFFICIENCY OF DIADROMOUS FISH

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## PREFACE

At IIASA through the project on Adaptive Resource Policies, and its successor, Integrative and Special Studies, we are experimenting with the use of modeling workshops, games and simulation models to assist managers in their efforts to achieve sustainable, high-productivity use of natural resources.

All of these approaches are based on formal models. To be useful these models must deal with important issues confronting current managers, and they should incorporate theoretically sound representations of the biological and physical issues that govern the behavior of the real resource system. This paper describes a model of fish productivity that meets both criteria.

Efforts to reduce the impact of dams on down-stream fisheries have been hampered by deficiencies in available models of river fish population dynamics. This paper, based on work carried out in two Moscow research centers, offers a significantly improved representation of migration and spawning as functions of fluctuations in river flow. The paper should be of special use to those who wish to moderate river flows without undue damage to commercially important fish populations.

Dennis Meadows
Leader, Integrative
and Special Studies
Project

ABSTRACT

A dynamic control model has been developed to describe the effect of the hydrological regime in a regulated river on the development of diadromous fish populations. Factors taken into account include finiteness of velocity of fish upstream and water downstream movements, nonuniformity of spawning area distribution along the river, riverbed profile, and the influence of water temperature on the spawning process. The model can help to obtain an optimal hydrograph of water outflow through the dam during the spawning period.

CONTENTS

## 1. INTRODUCTION

Valuable fish such as sturgeon, white sturgeon, and salmon, migrate between rivers and the sea during their life cycles. The negative consequences of water regime disruptions, such as the construction of hydropower stations on rivers, water pollution by industrial waste products, increasing salinization of seas, result in large fish losses. It is important to try to compensate for the influence of these factors in order to ensure successful fishery operation. In this paper the problem is studied using the example of fishery development in the lower Volga. The water regime in this region is complicated by a difference between the quantity of existing water resources and the high level of demand. Large volumes of water traffic, as well as floating timber use the rivers in this region. Moreover, industrial enterprises and irrigated agricultural areas are significant water consumers. The situation is made worse by competition between water uses including industry, power generation, agriculture, municipalities, fisheries. For example, ships or barges require fairly deep navigable channels and, therefore, a water level that is usually twice normal. The maximum capacity of hydropower stations is achieved at the expense of abnormally high water consumption in winter, so that fish populations are affected by reduced water levels in spring and in summer. Hydropower installations reduce spawning areas and change hydrological regimes in the river-sea system. Water level fluctuations caused by hydropower stations cause unfavorable effects, such as evaporation from the surface of reservoirs in summer. Such losses of water, together with irrigation, affects fisheries considerably. Also, industries and agriculture pollute the rivers with waste products and chemical fertilizers. Such high levels of water consumption can lead to a permanent lowering of sea level at estuaries and, in consequence, to an increase in salinity and a reduction in fish feeding grounds.

The situation in a river basin is very complicated. Changes in the water regime may cause stocks of valuable fish to decrease, while harvesting of other species increases. In order to compensate for the decrease in the former, large-scale measures have to be taken on rivers with regulated flows, such as improvement of spawning areas, building of fish-breeding enterprises, and rationalization of fishing strategies, in particular restricting fish catches at sea.

However, it is obvious that such steps are ineffective because they are small in scale and only local in character. The survival of the fishing industry thus depends upon the solution of numerous relevant problems related to large civil works, agriculture, transport, and related activities.

At the Computing Center of the USSR Academy of Sciences, in Moscow, a complex regional model has been created in which interactions among basic branches of the national economy in the region, with varying demands for water, have been taken into account. The model contains such blocks as hydropower engineering, agriculture and water use.

In this paper the fishery block is considered; this is connected to the rest of the model through the hydrological regime of the river. A dynamic model of fish population control, which describes the effects of regulated water flow on the populations of spawning diadromous fish has been constructed.

Several control problems have been formulated on the basis of the model, in which hydrological regimes and fishing strategies are control functions. The complicated mathematical nature of these problems gives rise to some pessimism about the practicality of direct theoretical analysis, so that at the initial stage, the model is used to simulate the regime. This provides an opportunity to estimate the effect of various hydrological regimes on features of the life cycle of the fish and to obtain satisfactory initial approximations of control functions. The latter will be applied in the near future for numerical investigations into the choice of appropriate structures and levels of fish populations.

## 2. DESCRIPTION OF THE MODEL

A long life fish population is considered which live in the sea and migrate upstream to spawn. It is assumed that in any given year, not all adults will migrate upstream to spawn, but the number will depend on the age of the fish. Thus, if the age structure of the population at the time t is characterized by the function $n(t,\tau)$, where $\tau$ is the age, then the number of fish entering the river to spawn at the same time can be described by function $D(\tau) \cdot n(t,\tau)$. The nonuniform distribution of migrating fish in time t is described by the Gaussian distribution function $F(t)$. The fishing strategy in the lower reaches of the river is described by $\phi(t,\tau)$. Thus, the number of fish of age $\tau$ that migrate at time t is expressed by

$$p(t,\tau) = n(t,\tau)D(\tau)F(t)[1 - \phi(t,\tau)] \quad .$$

Suppose first, that the spawning areas are distributed along the river in a definite way and second, that they are characterized by their useful space. At a given time t the spawning area S depends upon the volume of water passing through a given cross section. Suppose this cross section is situated at a distance z from the river mouth, and the speed of fish movement in the river, v, is approximately constant, then the fish that entered the river at $t - z/v$ will pass the cross section at t. If the distance between the river mouth and a dam is L and the average water velocity is C, then at time t the volume of water passing through the cross section will be t-(L-z)/C.

The main equation equation describing the spawning process as a function of the hydrological regime is:

$$\frac{\partial x}{\partial z}(t,z,\tau) + \frac{1}{v}\frac{\partial x}{\partial t}(t,z,\tau) = - w(x,t,z,\tau) \quad , \qquad (1)$$

where $x(t,z,\tau)$ is the number of fish at age $\tau$ at the cross section with coordinate z at time t, $w(x,t,z,\tau)$ is a so-called spawning strategy, i.e., the number of fish at age $\tau$ spawning at time t at the cross section z. The boundary condition corresponding to eqn. (1) is

$$x(t,o,\tau) = p(t,\tau) \quad . \qquad (2)$$

The function $w(x,t,z,\tau)$ determines the distribution of fish among different spawning areas and depends upon several factors, especially the hydrological regime during the spawning period.

The model of spawning area flooding serves to connect hydrological conditions in the spawning areas with the dam's outflow regime. To describe the unstable motion of the regulated river flow, St. Venan equations were used and these were simplified using some observed properties of the river flows we studied. As a result, the flow is considered to be almost stable, and the relationship between the volume of water u(t,z) passing through cross section z at time t, and characteristics of the riverbed is:

$$u(t,z) = \frac{\sqrt{i(z)}}{n} S(t,z)^{5/3} B(t,z)^{-2/3} \quad , \qquad (3)$$

where i(z) is the riverbed slope at the point z, S(t,z) is the cross-sectional area of the river at the point (t,z), B(t,z) is the width of the river at some point, and n is the riverbed roughness coefficient. In order to use expression (3) to calculate flooded spawning areas, the simplest riverbed profile is suggested in which the profile is assumed to be a trapezium based on a rectangle. The main parameters (width of rectangle a, height H, height of trapezium h, and $\alpha$ = the slope angle) can be obtained from characteristics of any river.

Expressing the values S and B in (3) through the riverbed parameters, obtain

$$u(t,z) = \frac{\sqrt{i}}{n} \frac{[a(H+h)+h^2\tan\alpha]^{5/3}}{(a+2h\tan\alpha)^{2/3}} \tag{4}$$

An effective width b(t,z) of flooded spawning areas at the point (t,z) may be calculated from

$$b(t,z) = \frac{2h(t,z)}{\cos\alpha(z)} \tag{5}$$

where h(t,z) were obtained from (4) as a result of a number of simplifications (by expanding the right-hand side with respect to to h/a and h/H):

$$h(t,z) = \frac{3H}{2}\left(\sqrt{1+\frac{4\tilde{u}(t,z)}{5u_o(t,z)}} - 1\right),$$

where $u_o(t,z)$ is the outflow corresponding to the case where the riverbed of width a and depth H is flooded, and

$$\tilde{u}(t,z) = u(t,z) - u_o(t,z)$$

In order to determine $w(x,t,z,\tau)$ it is necessary to define the number of fish passing through the given cross section that will spawn at this particular spawning area. We hypothesize in the model that the number that will spawn is proportional to the ratio of the flooded spawning area to the sum of all spawning areas upstream. If we accept a hypothesis of the linear dependence of the spawning strategy $w(x,t,z,\tau)$ of fish density $x(t,z,\tau)$ the function $w(x,t,z,\tau)$ will be

$$w(x,t,z,\tau) = f_1(t,z,T)\frac{b(t,z)}{\int_z^L b(t,z)\,dz}\,x(t,z,\tau),$$

where $b(t,z)$ is defined from (5), and $f_1(t,z,T)$ is a step function describing the effect of river water temperature on the spawning.

The quantity of fish roe at the point z at time t may be determined from a so-called birth equation:

$$y(t,z,o) = \int_{\tau_{min}}^{\tau_{max}} \beta(t,\tau) w(x,t,z,\tau) d\tau r \ , \qquad (6)$$

where $\beta(t,\tau)$ is the fertility coefficient and $[\tau_{min},\tau_{max}]$ is the productive age interval. The growth of young fish from roe at a spawning area at the distance z from the river mouth, is described by a so-called survival equation:

$$\frac{\partial y}{\partial t}(t,z,r) + \frac{\partial y}{\partial r}(t,z,r)$$

$$= -f_2(t,z,T)\chi[u(t,z)]\,\psi(t,z,r)\,\theta\left(\frac{y(t,z,o)}{b(t,z)}\right)y(t,z,r) \quad . \qquad (7)$$

Equation (6) will be the initial condition. Here $y(t,z,r)$ is the number of young fish of age r at point (t,z) (in volume of unit length). The functions $f_2(t,z,T)$, $\chi[u(t,z)]$ and $\theta\ [y(t,z,o)/b(t,z)]$ take into account the effect of water temperature, hydrological regime, and the roe density distribution on the hatching and survival rates of the roe, respectively. $\chi[u(t,z)]$ describes the rate at which roe are washed away when the flow increases sharply and, on the contrary, death caused from drying of the roe when the spawning areas dry out. The function $\psi(t,z,\tau)$ takes into account the effect of the destruction of young fish by predators. The appearance of functions $f_2,\chi,\psi$, and $\theta$ has been given in Luckyanov *et al.* (1982).

When the outflow is low, daily fluctuations in water volume in the area of a hydropower dam have a great influence on roe drying. A block describing daily water level fluctuations in the dam zone, determined by fluctuations in outflow volumes, is included in the model.

One of the control problems we treated can be formulated as a problem of obtaining a maximum "yield" of fish (which have reached an approximate age of $\tau_1$) from the given part of the river [o,L] during the time interval $[t_o, t_1]$. This "yield" can be expressed as an integral funcitonal

$$J = \int_o^L \int_{t_o}^{t_1} y\,(t,z,\tau_1)dtdz \quad , \tag{8}$$

where outflows u(t) through the dam act as control functions. These outflows must satisfy the natural restrictions:

$$u(t) \in G_u \quad , \tag{9}$$

and

$$\int_{t_o}^{t_1} u(t)dt \leq Q \quad . \tag{10}$$

It was mentioned above that the optimal control problem (1), (2), (6)-(10) can be solved numerically, resulting in optimal hydrological regimes corresponding to the maximum fish production. Such results are of academic interest. They may also be used to solve some important practical problems, such as estimating fish production losses caused by deviations in real hydrological regimes from their optimal values.

## 3. APPLICATION OF THE MODEL

The model was verified using a number of simulation experiments. For example, we studied species of spring sturgeon in the Caspian Sea, which spawns in the lower reaches of the Volga river. The time series in the model was five days and the Volga riverbed was divided into three spawning regions (zone 1 was furthest downstream). All spawning regions of the ith zone (i=1,2,3) are denoted by $m_i$ and the total area $S_j^{(i)}$ $(j=1,\dots,m_i)$ was replaced by a so-called effective spawning region, with an area $S_i$, located at a distance $L_i$ from the sea where

$$S_i = \sum_{j=1}^{m_i} S_j^{(i)} \ , \quad L_i = \frac{\sum_{j=1}^{m_i} S_j^{(i)} \cdot L_j^{(i)}}{S_i} \ , \quad i=1,2,3 \ ,$$

$L_j^{(i)}$ is the distance from the sea of the jth spawning region. At the first stage the stable (independent of time) population state was considered, i.e., $n(t,\tau) = h(\tau)$. The age distribution of sturgeons in the sea was modeled by

$$n(\tau) = \begin{cases} n_o \exp(-d\tau) \ , & \tau_o \le \tau \le \tau_s \\ n_o \exp\{-d\tau_s - \Phi a(\tau - \tau_s - \sqrt{b} \arctan \frac{\tau - \tau_s}{\sqrt{b}})\} & \\ \qquad \tau_s \le \tau \le \tau_{max} & \end{cases} \quad , (11)$$

where $\tau_s$ is the age at first spawning, $\Phi$ is a fishing policy (here assumed to be constant), and $n_o$, d, a, b are parameters determined according to experimental data. The function $n(\tau)$ can be described by the following curve:

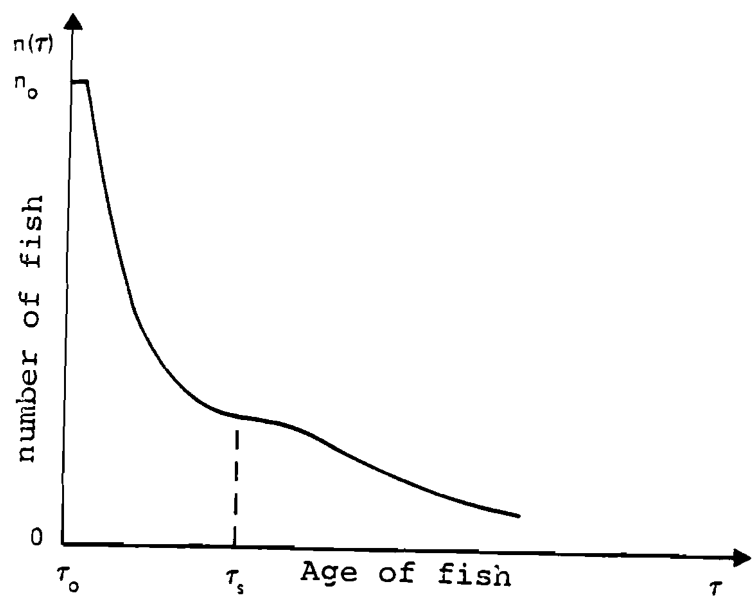


Figure 1. The age distribution of fish in the sea.

F(t) describes the time-dependence of adult fish introduced into the river for spawning, according to experimental data, and is expressed by the Gaussian function:

$$F(t) = \frac{1}{\sqrt{2\pi}\sigma} \exp\{-(t-t_{max})^2/2\sigma^2\} \quad . \tag{12}$$

It is known from experimental data that the maximum input of fish coincides with the "top" of the flood; thus $t_{max}$ is calculated by the model with

$$t_{max} = \min\{t \mid u = \max_t u(t)\}$$

The outflow function u(t) is as follows in discrete time.

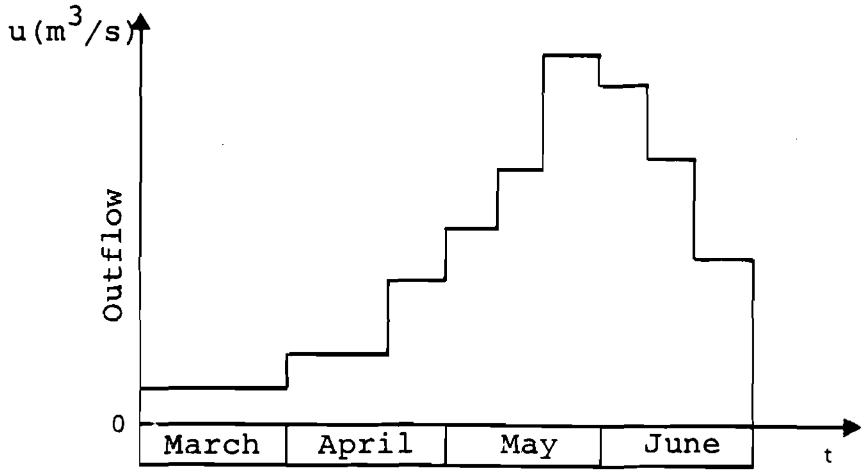


Figure 2. A typical hydrography of spring flood.

In Section 2 suggestions were made about water motion in the river; it was assumed to be almost stable. This means, first, that we neglected spreading of water outflow along the river bed, that is, if a volume u(t) is released from the dam at time t, then its flow at some downstream point z is

$$u(t,z) = u(t- \frac{L-z}{C})$$

In reality, a certain degree of spread can be observed, but calculations on the basis of observations have shown this is negligible. The influence of the spreading was estimated by the ratio

$$\gamma = \frac{u^1_{max} - u^2_{max}}{u^1_{max}} \cdot 100\% \quad ,$$

where $u^1_{max}$, $u^2_{max}$ are maximal outflows at two points. Over a period of a few years, with different water conditions, values of $\gamma$ varied between 15 and 24 percent. The appropriate water regimes for two points on the lower Volga are shown in Figure 3; the first point is quite near the dam, and the second is situated in the delta of the river.

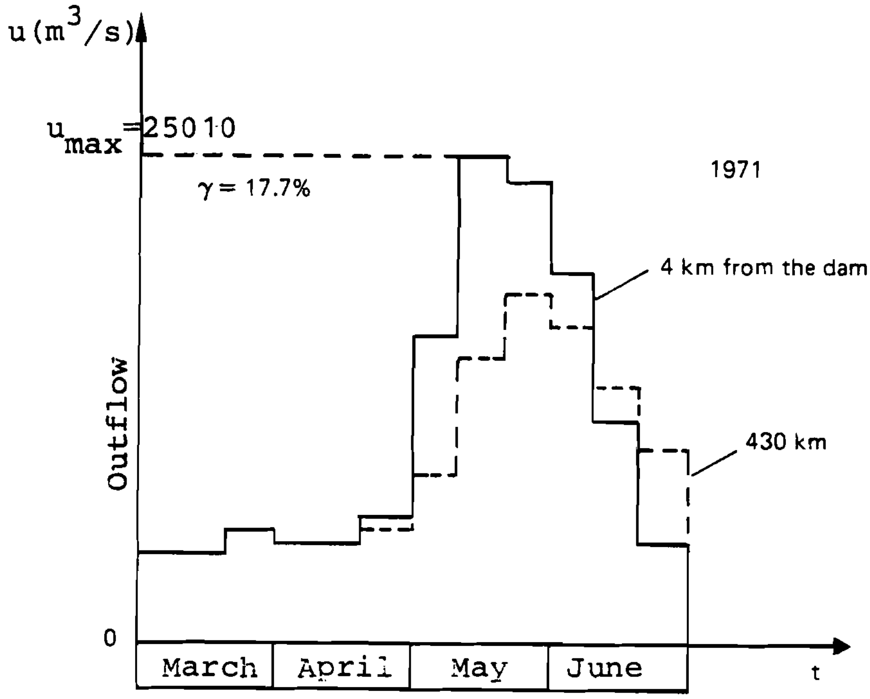


Figure 3. Spreading of water outflow along the river bed.

We also assumed that formula (3) is valid, i.e., that the level of water can be defined uniquely as a function of outflow. Many real curves H(u) were analyzed, and it was established that nonuniqueness determined by

$$\delta = \frac{\Delta H}{H_{max} - H_{min}}$$

is indeed negligible; this is illustrated in Figure 4. The temperature regime of river water can be approximated by the curve in Figure 5. The maximum temperatures occur at the end of June.

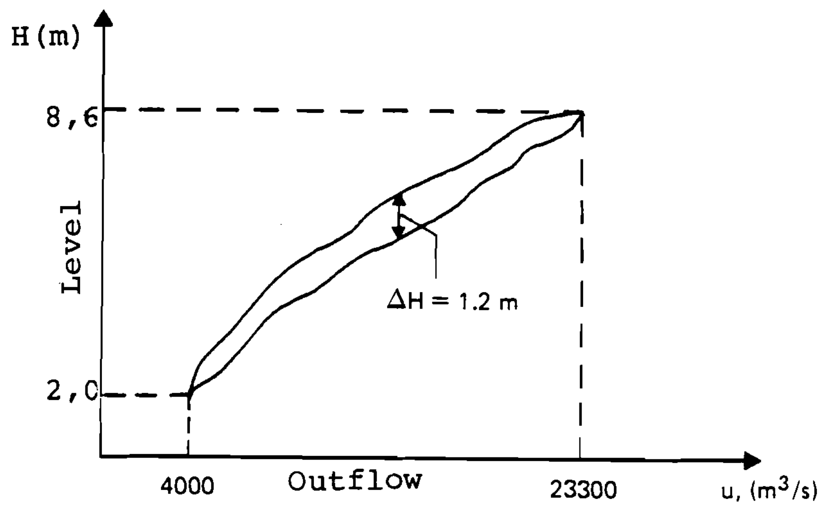


Figure 4. Nonuniqueness of level-outflow dependence.

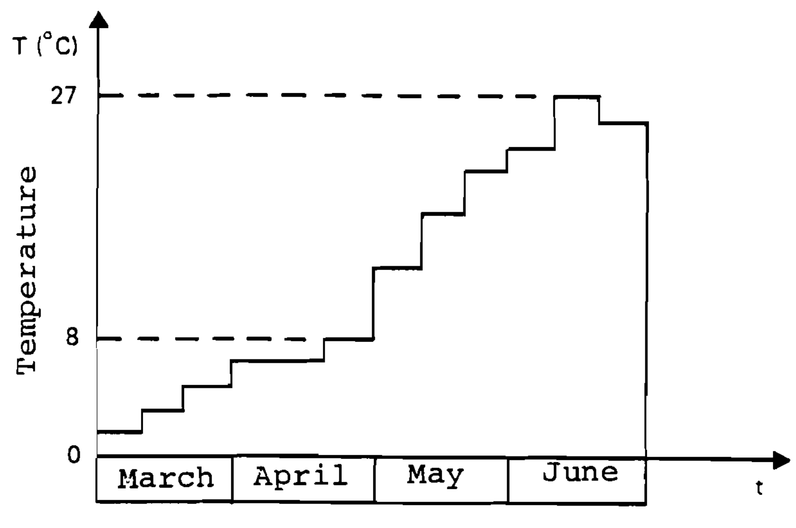


Figure 5. Typical temperature regime of river water.

If the temperature rises above 8°C after the end of April, then spawning is possible. Fish catches in the Volga estuary were, for the sake of simplicity, assumed to be constant from the beginning of April.

The age distribution of spawning fish corresponding to $n(\tau)$ is given in Figure 6, and it can be seen that the majority of spawning fish are 17 years old.

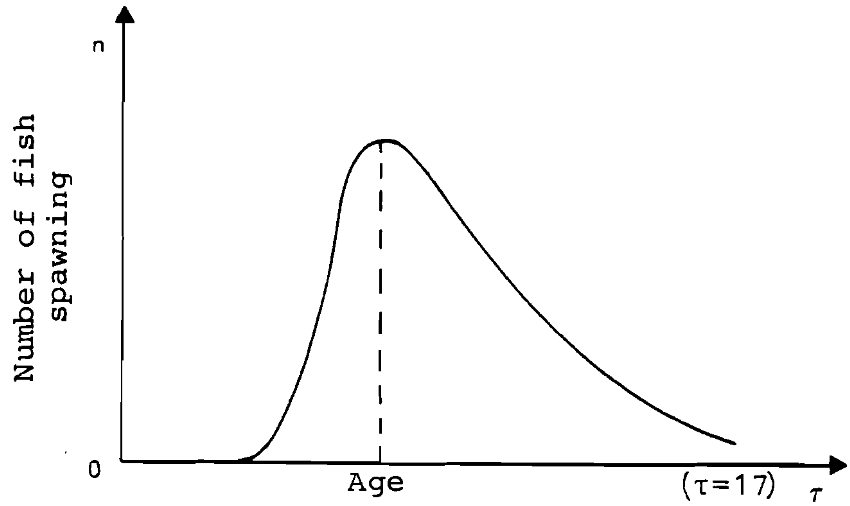


Figure 6. The age distribution of spawning fish

Real hydrological regimes of the Volga were used for simulation, and various water conditions were investigated. For each hydrological regime two integral characteristics were calculated: $\eta$, characterizing the influence of the regime on spawning effectiveness, and $\delta$, the coefficient of spawning area use.

The first characteristic was calculated in percentages and determined by destruction of roe due to unfavorable hydrological conditions by

$$\eta = \frac{J_{opt} - J_r}{J_{opt}}$$

$J_{opt}$, $J_r$ are the quantities of larvae corresponding to optimal and real water conditions respectively.

$\delta_i$ was calculated from

$$\delta_i = \frac{X_i}{\sum_{i=1}^{m} X_i}$$

where $X_i$ is number of fish hatched in the ith zone. The results from calculation are in good agreement with actual data. For example, the higher the outflow volume in a flood period, the higher will be $\eta$. The spawning efficiency is determined not only by the total volume of water, but also by its distribution over time. For the variant with the highest outflow volume, but with a sudden abatement, the spawning efficiency is less than for cases with lower outflow volume, the time distribution curve of which is smoother.

Preliminary calculations by ichthyologists on the basis of the model have shown that the model satisfactorily describes the main qualitative laws of sturgeon population growth. In another set of calculations, based on the real hydrographs block dealing with fish distribution between spawning regions has been removed. This block was based on the hypothesis of proportionality. Instead, we merely enumerated the ratios of fish populations in different spawning areas from our data which we found that the optimal fish distribution on spawning regions depends upon the volume of water flow during the year. Thus, it cannot be forecast. On the other hand, it has been discovered that the dynamical fish distribution on the spawning areas according to the proportionality principle (see formula for $w(x,t,z,\tau)$ page 5) always gives the number of surviving young fish that is close to optimal. Therefore, the model appears to be fairly reliable and it is a simple device that enables estimates to be made of the effects of various hydrological regimes of regulated rivers on the population of spawning diadromous fish.

Computer runs for two different years were made to check the adequacy of the model, and results of computations were compared with available information on spawning Volga sturgeon in previous years. The runs were made using data from the 1975 spring flood when the total water volume for April - June was 55.6 km3 (low water), and in 1966 when the flood volume was 156.5 km3 (high water). Hydrographs of the spring floods are shown in Figure 7.

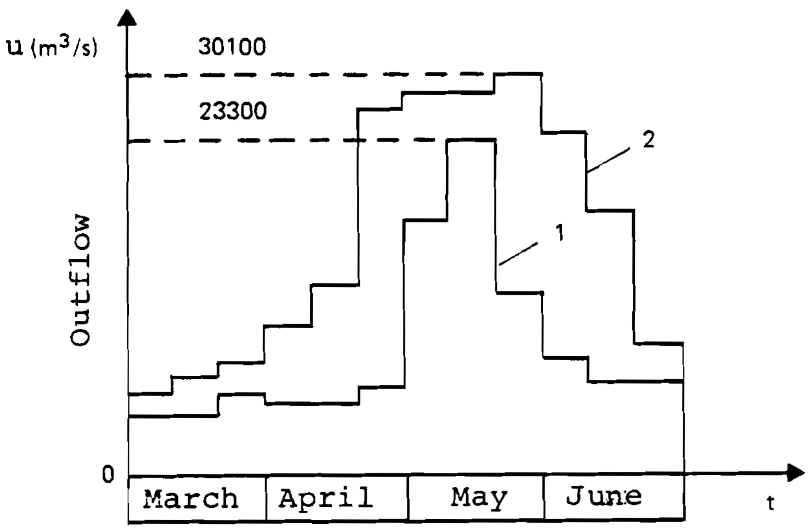


Figure 7. Hydrographies of spring floods for two contrasting years.

The number and the age structure of the spawning sturgeon population were assumed to be equal for both years, and temperature regimes were taken from *Hydrological Annuals* (1966, 1975).

Results of the computations were quite close to field data. For example, the time of spawning observed in spawning areas some 300-350 km (1975), 140 km (1966) from the Volgograd dam coincided with those obtained with the model. In Figure 8 are shown hydrographs of spawning sturgeon in 1966 at Kameny Yahr, 140 km from the Volgograd dam Curve 1, taken from Choroshko and Vlasenko (1970) describes field data, and curve 2 presents model data. As in 1975, the spring flood was high, and the spawning efficiency reduced; the total yield was half that of a good year, such as 1966. These results were confirmed by Choroshko (1972).

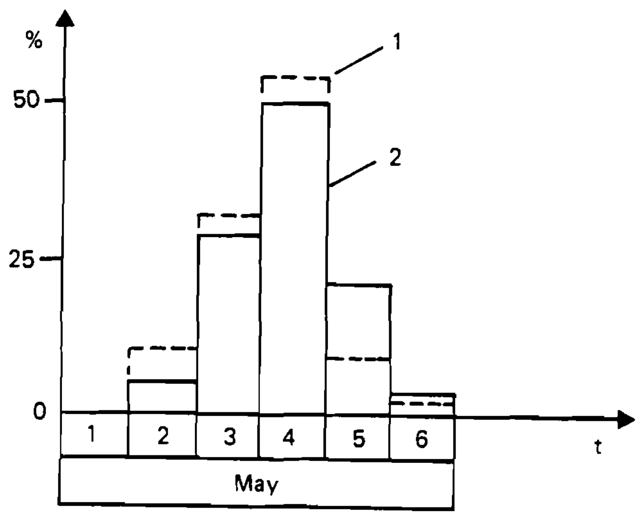


Figure 8. Sturgeon spawning in 1966 at Kameny Yahr spawning area (1: field data (Choroshko and Vlasenko 1970); 2: model results).

In 1975 the catastrophic death of 70-80% of sturgeon eggs caused by a sudden drying of spawning areas (due to the abrupt end the spring flood) was observed. This result was reproduced by the model. Dead sturgeon eggs amounted to 68 percent of the total spawned eggs killed. Model curves of young fish downstream coincided fairly well with the field data taken from Lagunova (1979).

Thus our experiments have shown that the model simulates the spawning dynamics of Volga sturgeon quite well and that it correctly describes the influence of water flow regime on the river below the Volgograd dam.

With the help of the program an optimal water flow regime through the Volgograd dam was calculated, in which the total volume of passing water was assumed to be constant. The search for the optimal regime included the checking of every possible form of hydrograph. The following factors were taken into account:

(a) minimum guaranteed flow ($u_{min}$);

(b) volume of additional flow needed to produce a flood (W);

(c) flow volume increment (dH);

(d) time increment (dT);

(e) initial position of additional flow on the time axis ($T_o$);

(f) hydrographic position shift on the time asix ($\Delta\tau$);

(g) the maximal allowed hydrographic shift on the time axis ($\tau_{max}$).

Simulation results are given in Figure 9, for the following:

$u_{min}$ = 4500 $m^3$/sec

W = 20.7 $km^3$

dH = 4000 $m^3$/sec

dT = 10 days

$T_o$ = beginning of May

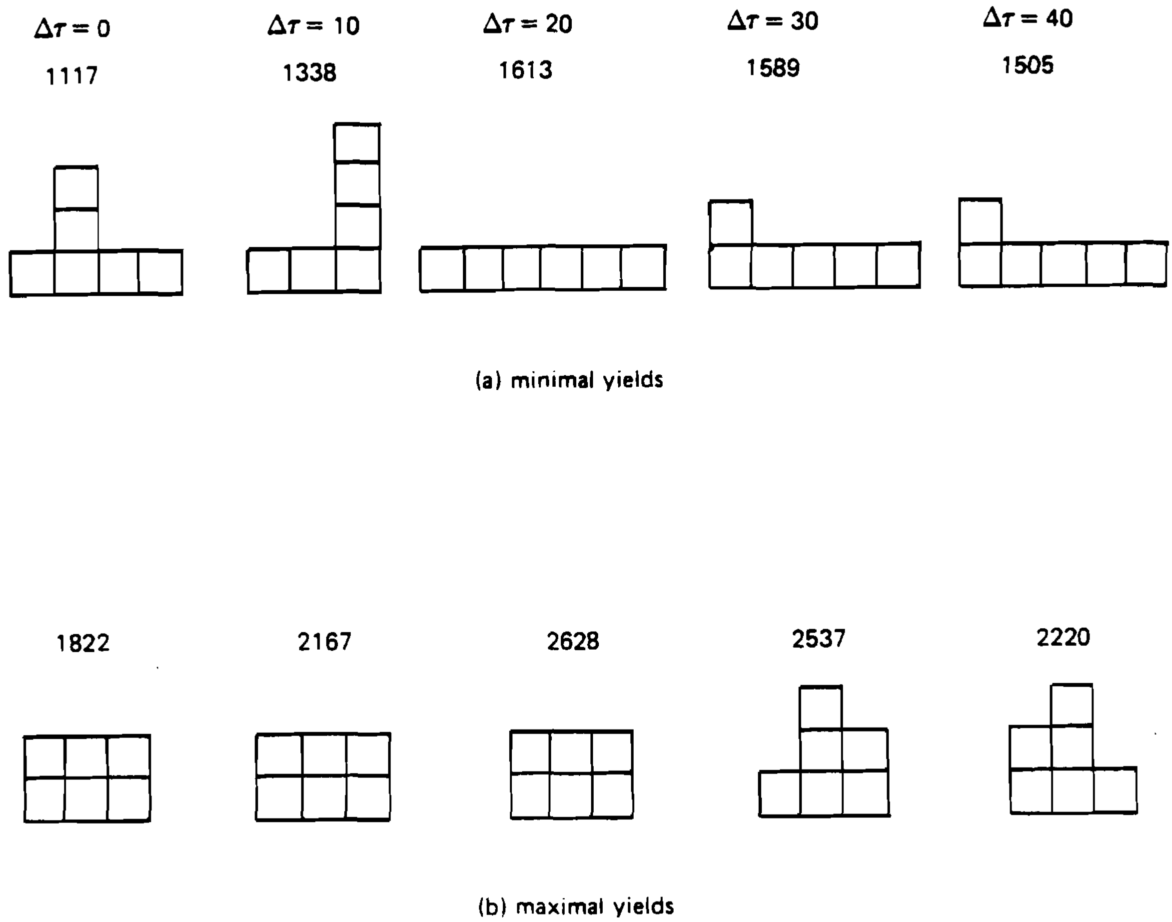


Figure 9. Hydrograph of water flow regimes: (a) minimal yields (b) maximal yields. The numbers of sturgeon larvae are in millions. $\Delta$ = 10 days; $\tau_{max}$ - 40 days.

These values simulate a low water regime, like that observed in 1975.

The water temperature and numbers of spawning fish were considered to be constant for all water regime variants.

The experiment showed that the sturgeon spawning efficiency is determined by the water flow regime; in fact, the yield can be doubled, if the regime is improved (see Figure 9).

The most important characteristics of a water flow regime, apart from water volume, are: (a) the hydrograph, and (b) its peak on the time axis ($\Delta\tau$). A change in the hydrograph can change the yield by 50 percent. The worst results are when the hydrograph has either a peak maximum or is long and flat. Optimal values were given by "compact" hydrographs.

A coincidence of a flood with ideal spawning temperatures also affects spawning efficiency, as confirmed by our experiments. Discrepecies can be characterized by $\Delta\tau$; a shift in $\Delta\tau$ first gives an increase in yield. Then it gives a decrease. This result is true both for minimal and for optimal yields.

## 5. CONCLUSIONS

(1) A dynamic control model was constructed to describe the influence of hydrological regime in a regulated river on the development of diadromous fish populations.

(2) Numerous model runs have shown that it describes satisfactorily the main processes of diadromous fish behavior in a regulated river.

(3) The model can be applied to assess the effects of various hydrological regimes on the structure and size of diadromous fish populations. One can also use the model to assess the damage caused by a less than optimal water flow regime.

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